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E-HUB
Energy-Hub for residential and commercial districts and transport

SEVENTH FRAMEWORK PROGRAMME

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D2.1. Inventory of existing technologies for energy storage and conversion

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Content

Executive Summary

The E-Hub project, funded under the FP7 programme "Energy efficient Buildings (EeB)", aims at developing energy infrastructure concepts that are able to utilise the full potential of renewable energies available at district level.

In an E-hub system, with smart control of energy consumers and energy producers, power and heat generating systems are expected to operate differently from stationary systems running at nominal conditions, as is currently the case e.g. in large electricity plants. Therefore, intermittent operation, start-up behaviour and operation at partial load are important aspects.

In the present document, an inventory is made of existing technologies for generation, storage and conversion of energy, with an emphasis on characteristics determining the possible role of such technology in an E-hub system.

The technologies considered are described in chapters 2-7, containing a short description of the technology, a picture of the technology, a graph (COP, efficiency), a number of KPI´s (Key Performance Indicators) and information on modeling (a set of equations describing the system).

More detailed information, including data on commercially available equipment, is given in Annexes A-C, with Annex D specifically comparing ATES (Aquifer Thermal Energy Storage) and BTES (Borehole Thermal Energy Storage). The technologies are summarized in the tables below including the KPI's given for each technology.

Electricity Generation (chapter 2)	
Technologies PV Wind Energy Deep Geothermal.	KPI (Key Performance Indicator) Power range Primary energy use Cost of the equipment Efficiency Modelling equations
Heat Generation (chapter 3)	
Technologies Boiler Electric Resistance System Solar Thermal Heat Pump Geothermal	KPI (Key Performance Indicator) Power range Cost of the equipment Efficiency (PER/COP) Modelling equations
Cogeneration (chapter 4)	
Technologies Organic Rankine Cycle (ORC) CHP based on ICE (Internal combustion Engine) CHP based on External Combustion Engines (Steam) CHP based on External Combustion Engines (Stirling) CHP with Steam Injection Gas Turbine (STIG) and Heat Recovery Steam Generation (HRSG) CHP based on Fuel Cells and Gas Reformer CHP based on Hybrid PV/Thermal	KPI (Key Performance Indicator) Power range Cost of the equipment Efficiency (PER) Temperature Modelling equations
Cooling Generation (chapter 5)	
Technologies Compression Chiller Absorption Chiller	KPI (Key Performance Indicator) Power range Cost of the equipment Efficiency (PER/COP) Temperature Modelling equations

Table Inventory of generation technologies to be used in an E-hub system including the KPI (Key Performance Indicators) considered.

Thermal Energy Storage (chapter 6)	
Technologies Sensible Heat Aquifer Thermal Energy Storage (ATES) Borehole Thermal Energy Storage (BTES) Energy Pile Cavern Thermal Energy Storage (CTES) and solid storage media Latent Heat Phase Change Materials (PCM) Chemical Heat Storage	KPI (Key Performance Indicator) Capacity Power range Cost of the equipment Efficiency Storage time Temperature range Number of cycles Modelling equations
Electrochemical Energy Storage (chapter 7)	
Technologies Batteries and Flow Batteries Hydrogen Storage and Generation Systems	KPI (Key Performance Indicator) Capacity Power range Cost of the equipment Efficiency Storage time Number of cycles Modelling equations

Table Inventory of storage technologies to be used in an E-hub system including the KPI (Key Performance Indicators) considered.

In the next step, the different technologies are compared. As an illustration, the table below compares the KPI's for heat generation. The tables are given in chapter 8.

Component type		Efficiency		Power Range	Cost
Boiler		85-95%	PER	Few kW up to large boilers for power generation	< 50 €/kW th
Electric resistance systems		38-40 % [2]	PER	Few kW up to large furnaces	100 €/kW
Solar Thermal	**Solar collectors**	n/a		0,8-0 kW/m^2	200-1.000 €/kW
	Road Thermal collectors	Thermal performance <30% (based on solar irradiation)		n/a	100-160 €/kW
Heat pump		Electric: 2.5 – 5.0	COP	Few kW up to several MW	240 €/kW
		100 – 200 % [2]	PER		
		Engine: 0.8 – 2.0	PER		
		Thermal: 1.0 -1.8	PER		
Geothermal		Electric: 20	COP	n/a	n/a
		800 % [2]	PER		

Table Comparison of heat generation technologies to be used in an E-hub system.

From the comparison, the following conclusions can be drawn.

In the field of **electricity generation**, Deep Geothermal is generally applied for high power productions (>10 MWe), which makes it less suitable for an E-hub system on district level. PV and small wind turbines are the most suitable technologies to be applied in the E-Hub system. The performance of those technologies are climate dependent, so the availability of solar and wind energy should be studied in more detail for each individual location and the E-hub system has to be able to deal with the fluctuating nature of the energy supply.

Among **heat generation** technologies, the most promising technologies based on the efficiency and cost are boilers and heat pumps. Boilers have been applied for a long time, both for space heating and domestic hot water production and they are very robust. In addition, gas boilers allow short on-times of 1 – 2 minutes without serious efficiency drop or wear. In combination with the low investment costs, this makes them ideal as a back-up heater in E-hub systems.

Heat pumps show higher PER than boilers, especially for heating, but the performance depends strongly on correct dimensioning and implementation of the whole system (including the heat source). Heat pumps need to be operated with on-times of at least 5 minutes in order to prevent efficiency drop and wear, resulting in a limitation of life span. This is an aspect to become relevant in a smart energy supply system.

Heat pumps are applied for lower delivery temperatures than boilers and they can be applied in combination with renewable energies for heat production. Due to the high investment costs, heat pumps are almost always operated with an additional (electrical resistance) back-up heater. The optimal control of this type of systems may be a subject in the E-hub study.

Electrical resistance systems are cheap and flexible, but they suffer from a low PER (Primary energy Ratio) when power generation is taken into account. Finally, solar thermal generation technologies have lower performance and they are relatively expensive but they use a non-costly energy source, which makes this technology interesting.

Different **cogeneration** or CHP (Combined Heat and Power) technologies are available in a power range starting at 1 kW_e. In general, the electrical efficiency is higher for higher nominal powers, resulting in higher overall efficiency.

When a CHP is used (which can be biomass fired), the objective is to maximize its contribution to the total energy demand. Since CHP's are generally heat demand driven, with excess electricity exported to the grid, the E-hub control system should be able to allow a temporal shift in heat demand and to store excess heat into buildings, advanced heat storage systems or underground heat storage.

Electrically driven compression chillers are widely applied for **cooling generation**, using air and water as media at condenser and evaporator. Energy performance is depending on both the chiller quality and temperature levels at condenser and evaporator. Absorption chillers are little applied, requiring heat (hot water) at a temperature level of 85 °C or more. When solar heat or waste heat at a relative high temperature level is available, this technique may be interesting.

Since all cooling generators require prevention of short cycle times and to operate as much as possible in steady state, the objectives for the cooling function in an E-hub system are minimization of cooling demand and flattening the cooling power profile using cold storage systems and using the building's thermal mass as a buffer.

In the field of **thermal energy storage**, as well as storage time, there are a lot of temperature ranges and also price ranges, which will influence the selection of the most suitable technologies. For all systems, storage losses are a limiting factor.

Storage systems for DHW are most common, in general as storage for a few hours up to one day. In combination with solar collectors, heat storage for several days may be interesting. The E-hub system needs control systems to optimize the use of these heat sources and the available storage volume, respecting the minimum storage and temperature demands.

Several systems can be used for thermal storage:

- Building heat capacity. This may be enlarged by applying PCM's (Phase Change Materials) in the building structure.

- System heat capacity. As a kind of extension of the building heat capacity, heat storage systems may be added, e.g. in the form of distributed storage or in the form of TCM's (Thermo Chemical Materials) allowing prolonged storage without any heat losses. Both are studied in task 3.2 of this project.

- Seasonal storage. This requires large volumes, which could be a crucial factor to determine its suitability for the application to the E-hub systems. ATES and BTES systems may be considered as a natural type of seasonal storage, with storage temperatures in general close to the undisturbed soil temperature (± 10°C).

In the field of **electrochemical energy storage** there are several technologies available, differing in capacity, life cycles and cost. However, a detailed study is outside the scope of this report because electrical storage was explicitly excluded in the DOW. We will however, include electrical storage (e.g. in the form of a black box) in our simulation of the district's energy infrastructure to see if electrical storage can improve overall efficiency of an E-hub system.

Hydrogen storage and generation is a rather expensive technology. In addition the efficiency of a complete cycle (electricity into Hydrogen using electrolysis and back into electricity using e.g. a Fuel cell) is low. Nowadays it is only convenient for off-grid applications to use and manage any surplus of renewable energy.

The outcome of this document will be used as input to task 2.3: "*Definition of possible district scenarios and optimization process*" and task 2.4: "*System impact calculation*" of this project.

1. Introduction

E-hub concept can be defined as the physical cross point, similar to an energy station, in which energy and information are interconnected, and where the different forms of energy can be managed, converted into each other and/or can be stored.

Nowadays, there is a lack of utilisation of the full potential of the renewable energy at district level. The ambition of the E-hub project is to use the potential of renewable energies up to covering 100% of the energy demand on district level. E-hub will exchange energy via the energy grids between the different actors (who may be a consumer at one time and a supplier at another time). The consumers and suppliers will exchange information on their energy needs and energy production with the energy hub, the hub then will distribute the energy available in the most efficient way. For proper matching of supply and demand, the E-hub will use conversion and storage of energy, as well as load shifting.

The aim of the E-hub project is to develop the e-hub as a system, to develop technologies that are necessary to realize the system, to develop business models in order to overcome institutional and financial barriers, and to demonstrate an E-hub in the form of a real situation and in a few case studies/feasibility studies.

The objective of the present document is to make an inventory of existing technologies for energy storage and conversion, with emphasis on the appliance characteristics determining the possible role of an appliance in an E-hub system.

In addition in Annex D an overview of all relevant data including data relating to dynamic behaviour are given.

The outcome (data) of this document will be used as input in Task 2.3. Definition of possible district scenarios and Task 2.4. System impact calculation.

2. Electricity Generation

2.1. Photovoltaic

A PV module (photovoltaic module) is a device that converts solar irradiation to electrical energy. Several types of PV modules are marketed:

Wafer based modules: This concerns crystalline silicon modules: these modules are the most common modules on the market. Monocrystalline and polycrystalline (or multicrystalline) modules are under production.

Thin film modules: Several types of thin film modules are on the market, such as amorphous silicon modules, CIS modules and CdTe modules.

Figure 1. Different types of PV modules

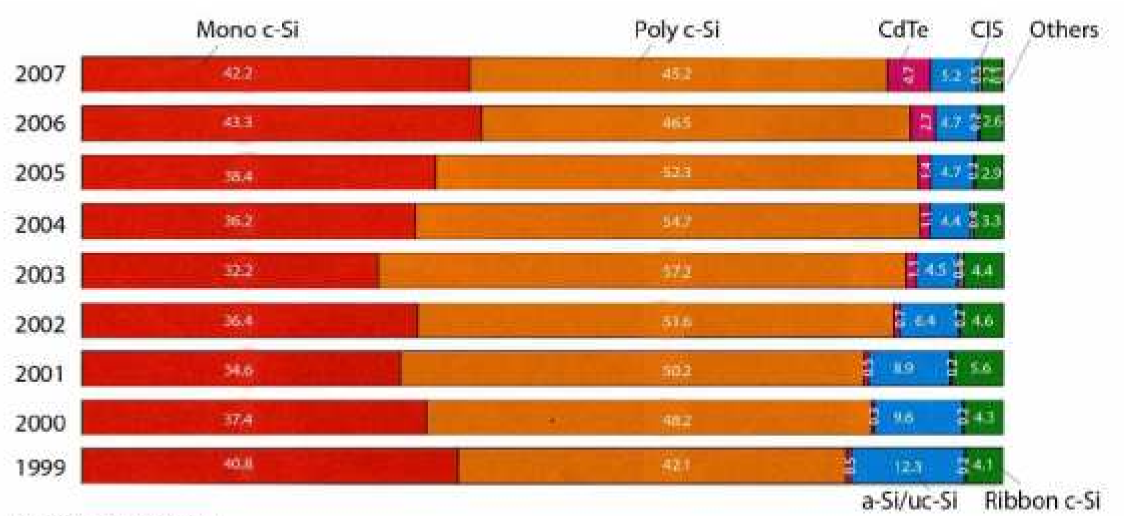


Figure 2. Overview of PV technology global market shares up to 2007 (Ruoss, 2008).

Typical efficiencies for these modules are shown in Figure 3

type of cell	range commercial module efficiencies
multicrystalline Si	11-15%
monocrystalline Si	10-17%
HIT cells	16-17%
ribbon & EFG cells	12-13%
a-Si (single junction)	4-6%
a-Si (triple junction)	5-7%
CIS	9-11%
CdTe	6-9%

Figure 3. STC Efficiency range of commercial modules (data 2005).

The yield of a PV module can be calculated from:

$$P_{PV} = \eta_{module,STC} * A_{module} * I_{solar} * C_{irr} * C_T * \eta_{inverter(P)} \qquad (2.1.1)$$

Here, $\eta_{module,STC}$ is the module efficiency under Standard Test Conditions (STC), which is an irradiance of 1000 W/m2 and a temperature of 25℃, and values can be found in Figure 3. A_{module} is the module area in m2, I_{solar} is the solar irradiance in W/m2. C_{irr} and C_T are corrections to the module performance, due to low irradiance or temperature; with low irradiance or high temperatures the module efficiency declines. The low irradiance effect is shown in the figure below.

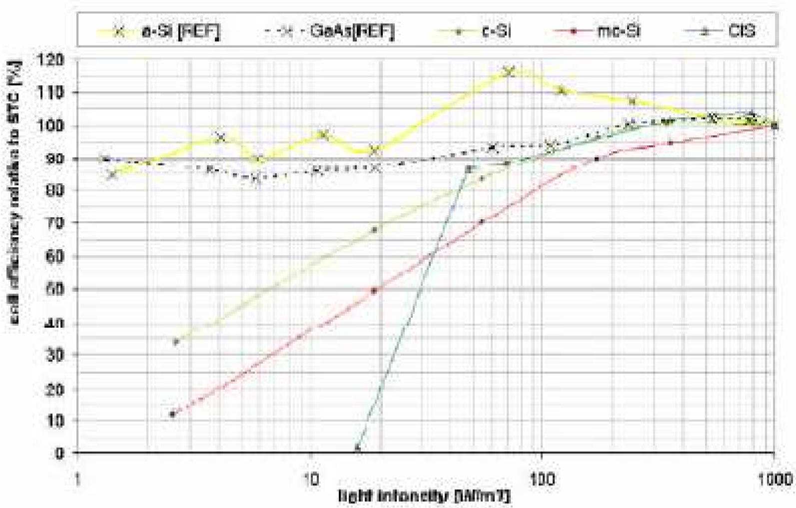


Figure 4. Effect of low irradiance on cell efficiency (Reich et al., 2005). Note the logarithmic scale!!

The temperature correction is given by

$$C_T = (1 - \beta (T - 25^oC)) \qquad (2.1.2)$$

In which the value of β is a constant that is specific for the different module technologies, as shown below.

type of cell	temperature coefficient (based on power)
crystalline Si	0.4%/K to 0.5%/K
a-Si	-0.2%/K
a-Si	-0.2%/K
a-Si	-0.21%/K
a-Si/µc-Si hybrid	-0.23%/K
CIS	-0.36%/K
CdTe	-0.25%/K

Figure 5. Temperature correction coefficients for different PV module technologies.

Finally, the inverter efficiency (η inverter) is a function of the power, and depends on the specific inverter design and design power. Below, two typical inverter curves are shown. Note that the location of the maximum in the curve depends on the design power for the inverter; for smaller design powers the maximum efficiency is at lower output powers.

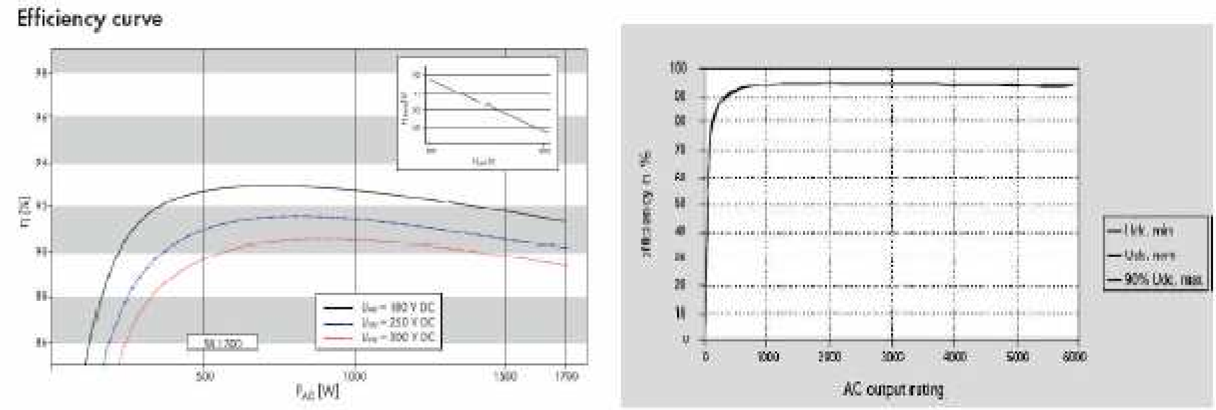


Figure 6. Inverter efficiency curves (a) Sunny Boy 1700 W inverter, (b) Sunmaster QS 6400 W inverter.

In the annual PV performance, all these effects are included in the Performance Ratio, which is defined as the final production, divided by the reference production. Typically, the actual performance of a PV module is in the order of 70-80% of the reference performance (see Figure 7).

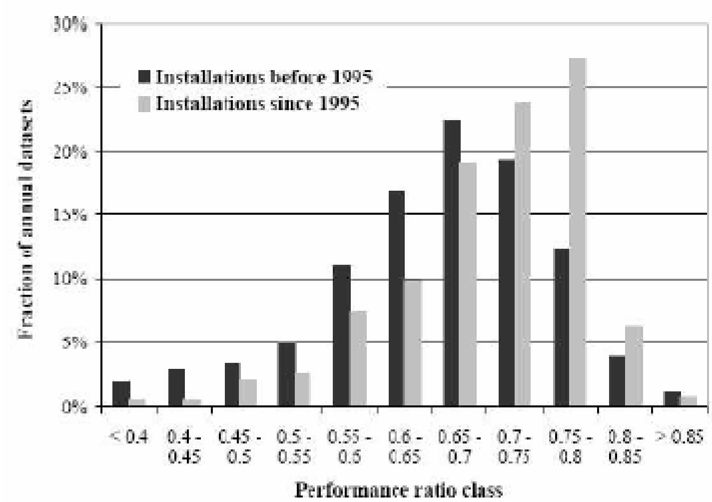


Figure 7. PR for 334 monitored grid-connected PV systems (Jahn, 2003).

Key performance indicators:

- Power range (W): 0-160 W/m2.
- Primary energy used: none (only embodied energy in PV manufacturing)
- Cost of the equipment (€/kW): 2500-3000 euro/kW (retail module price, excluding installation costs; see Figure 8).

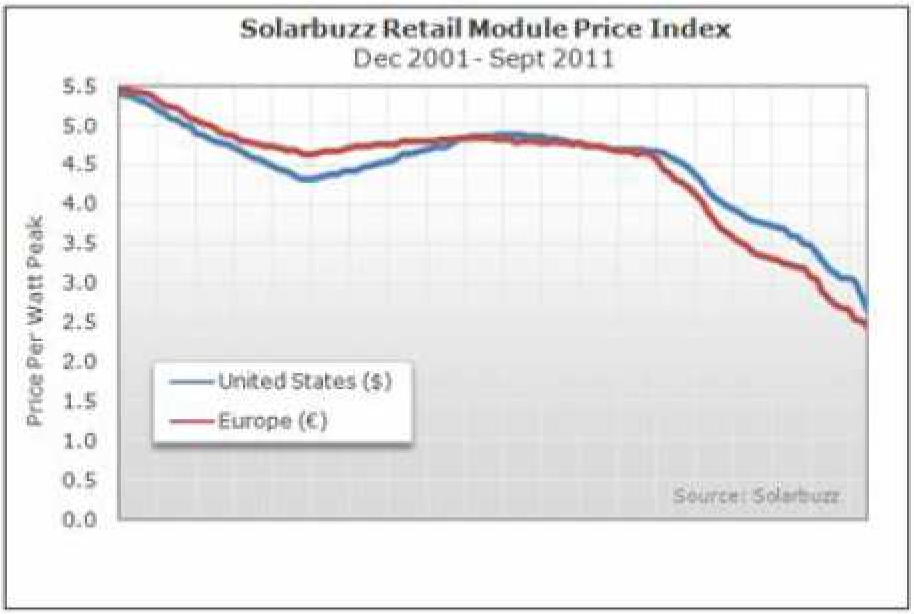


Figure 8. Cost of PV modules (from solarbuzz.com/facts-and-figures/retail-price-environment/moduleprices

2.2. Wind Energy

Wind turbines transform the kinetic energy of moving air into useful work. There are two main types of turbines:

Horizontal axis wind turbines
In these turbines the rotor is mounted on a horizontal axis. The rotor needs to face the wind direction by means of a tail or active yawing by a yaw motor. Horizontal axis wind turbines are sensitive to the changes in wind direction and turbulence which have a negative effect on performance (due to the required repositioning of the turbine for facing the wind flow). The best locations for these turbines are open areas with smooth air flow and few obstacles.

Figure 9. Horizontal axis wind turbines

Vertical axis wind turbines
Vertical axis wind turbines are usually developed only for the urban environment. Changes in wind direction have fewer negative effects on this type of turbine because it does not need to be positioned into the wind direction. It is important to notice than the overall efficiency of these turbines in producing electricity is lower than horizontal axis wind turbines.

Figure 10. Vertical axis wind turbines

A mathematical model able to describe the wind turbine behaviour can be divided in the following subsystems:

- Wind resource model
- Aerodynamic conversion
- Generator model

Wind resource model

The wind speed profiles can be described by using the Weibull distribution which accumulative function is shown beside.

There are some parameters to adjust this model and compensate the deviation:

- Horizontal correction due to errors committed during the wind measure campaign.

- Height correction: due to the variation of the wind with the altitude. It can be expressed with the following equation:

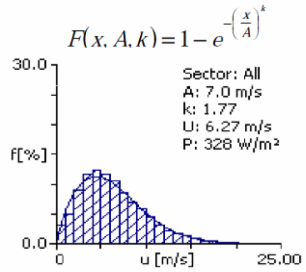


Figure 11. Weibull distribution

$$V(z) = V(z_{ref})\left(\frac{z}{z_{ref}}\right)^{\alpha} \qquad (2.2.1)$$

The value of alpha depends on the surrounding profile (urban, open sea etc...)

- Site correction: in order to calculate the wind speed at the specific location of the wind turbine, existing wind data can be extrapolated by using this formula:

$$V_{ref} = V_{met}\left(\frac{\delta_{met}}{H_{met}}\right)^{\alpha_{met}}\left(\frac{H}{\delta}\right)^{\alpha} \qquad (2.2.2)$$

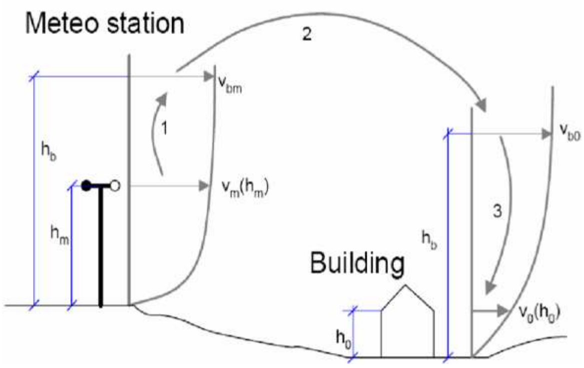


Figure 12. Site correction

Table 1. Site correction table

Terrain category	Description	Exponent a	Layer thickness δ (m)
1	Large city centers, in which at least 50% of buildings are higher than 21 m, over a distance of at least 2000 m or 10 times the height of the structure upwind, whichever is greater	0.33	460
2	Urban and suburban areas, wooded areas or other terrain with numerous closely spaced obstructions having the size of single-family dwellings or larger, over a distance of at least 2000 m or 10 times the height of the structure upwind, whichever is greater	0.22	370
3	Open terrain with scattered obstructions having heights generally less than 10 m, including flat open country typical of meteorological station surroundings.	0.14	270
4	Flat, unobstructed areas exposed to wind flowing over water for at least 1.6 km, over a distance of 500 m or 10 times the height of the structure inland, whichever is greater	0.10	210

In order to minimize the loses for turbulence a wind rose must be developed with the following data in each sector:
- Turbulence intensity
- Frequency
- Extreme velocities
- Orography
- Extrapolation for future years

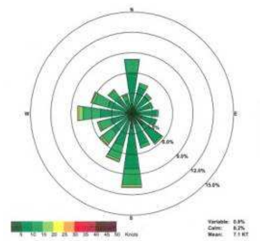


Figure 13. Wind rose

Wind blade performance

The kinetic energy from wind is transformed in mechanic movement through the blade. A blade is an aerodynamic profile and the amount if energy extracted can be explained through the energy and force balance:

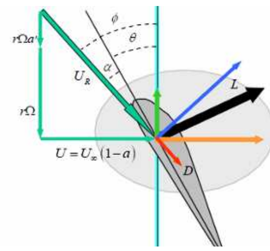
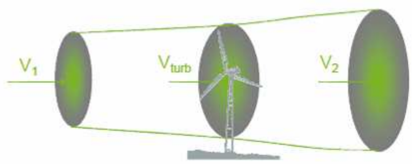


Figure 14. Forces balance

The simplest model is the Betz`s law. A further develop should involve CFD and finite element calculation processes.
Betz’s law is the theory that explains the maximum possible energy to be derived from a wind turbine.
According to this law the maximum efficiency of a wind turbine is the 59,3% of the kinetic energy.



$$P_{max} = \frac{1}{2}\rho V_1^3 \frac{\pi D_{Rotor}^2}{4}\frac{16}{27} \quad (2.2.3)$$

The model is explained using the factors the performance coefficient Cp of the turbine that is the mechanical output power of the turbine divided by wind power and a function of wind speed.

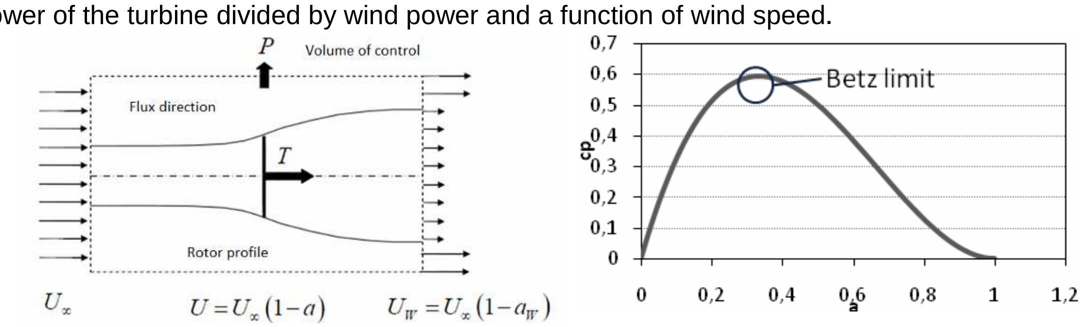


Figure 15. Betz’s mathematical model

$$P = \rho S U_\infty^3 2a(1-a)^2 \Rightarrow C_P = \frac{P}{\frac{1}{2}\rho S U_\infty^3} = 4a(1-a)^2 \qquad (2.2.4)$$

Being $a = v_2/v_1$

For a particular wind turbine, where the nominal power P_nom and the nominal velocity V_nom are known, the reference power at the reference velocity (average wind speed or instantaneous wind speed) can be calculated with the following equation:

$$P_{ref} = \left(\frac{V_{ref}}{V_{nom}}\right)^3 P_{nom} \qquad (2.2.5)$$

- **Generator model**

The most common electric generators used in wind turbines are:

Variable-speed system, induction machine with squirrel cage rotor
Variable-speed system, induction machine with wound rotor
Variable-speed system with synchronous machine

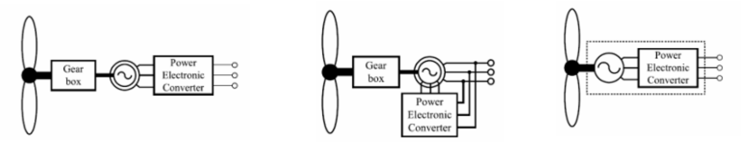


Figure 16. Generators

Each manufacturer provides the turbine production with wind speed dependence as shown in next figure for Vestas V90 wind turbine.

To select the most suitable wind turbine wind and machine models are compared. In the figure bellow

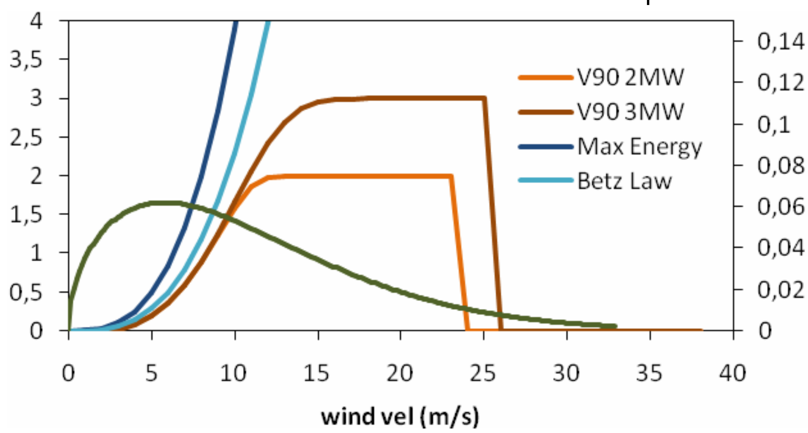


Figure 17. Air turbine performance and wind distribution

The most common used models available in the market are: Wasp, WindFarmer, Meteodyn, Windsim and Open Wind.

The initial investment for large wind turbines is about 1.0 €/W for land installations and about 2.0 €/W for offshore.

Regarding urban wind turbines, the investment per kW can vary a lot between the different models. According to the information provided by manufacturers, the range comprises values between 2.4 and 9.1 €/W.

The expected yield, assuming there is an average wind speed of 5.5 m/s, would very approximately amount to 150 - 400 kWh/m2/year. The yield of large turbines varies between 800 and 1200 kWh/m2/year.

2.3. Deep Geothermal

In general, geothermal power generation utilizes the heat from the earth geological layers. Thermal energy can be used directly, or used for electricity production. It is good to note that geothermal power generation can be considered as a renewable energy source only if the heat extraction rate does not exceed the reservoir replenishment rate. [1]
Highest energy resources locate mainly close to boundaries between lithospheric plates, where visible geothermal activity exists frequently (such as hot springs, fumaroles, steam vents, and geysers). According to Barbier (2002) the most important features of a good resource location are:

1) a high temperature (for high power plant efficiency)
2) a large quantity of stored heat (for resource longevity) and
3) reinjection well sites available at a lower elevation than production (for disposal under gravity).
4) Low rate of liquid production per unit of energy

The process of utilizing the thermal energy from the ground is illustrated in figure 18. Geothermal power generation is based on a reservoir, which is a sufficiently large body of permeable rocks at a depth accessible by drilling. The rock has to contain large amounts of fluids, water or steam, which carry the heat to the surface. Boiling is the most efficient mechanism due to the high heat transfer rates of vaporization and the high heat capacity of steam. The reservoir is bounded by cooler rocks hydraulically connected to the hot reservoir by fractures and fissures, which provide channels for rainwater to penetrate the reservoir. These cooler rocks crop out at the surface, where they represent the so-called recharge areas of the geothermal reservoir. Thermal waters or steam are, in fact, mainly rainwater that infiltrates into the recharge areas at the surface and proceeds to the depth of the reservoir, increasing the temperature while penetrating the hot rocks of the reservoir. After utilizing the thermal energy, the spent cooled fluid has to be disposed. Typically more than 95 % of it is reinjected into the reservoir as water, aiming to limit pressure losses and to replace at least part of the fluid extracted. As a result, the geothermal system is cooled with the same amount of energy than heat is utilized, excluding the natural heat inflow to geothermal system. However, the geothermal resource volume is large and hence, it allows the usage of the geothermal resource for many decades. [1]

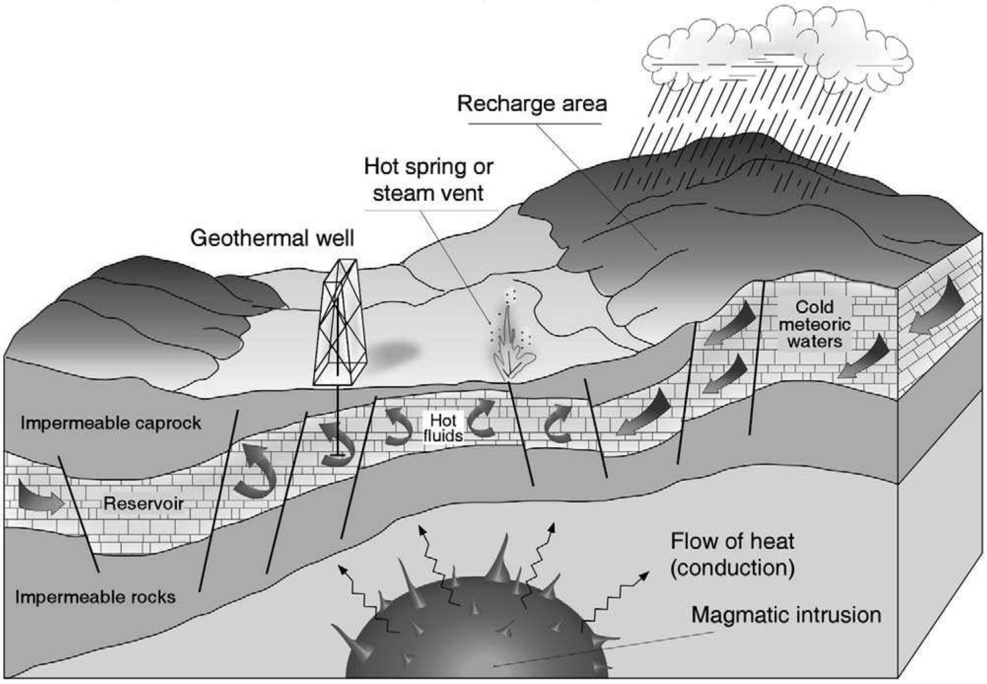


Figure 18: A geothermal steam field with its elements: a recharge area, an impermeable cover, a reservoir, and a heat source. [1]

There are several ways to produce electricity from geothermal energy, either from the vapor or from hot water from the geothermal wells (see figure 19). The efficiency of the generation of electricity from geothermal steam ranges from 10 to 17%. According to Barbier (2002), the simplest and cheapest of the geothermal cycles used to generate electricity is the direct-intake non-condensing cycle, in which the steam from the geothermal well is simply passed through a turbine and exhausted to the atmosphere. This system consumes about 15–25 kg of steam per generated kWh and it is used if the content of noncondensible gases in the steam is greater than 50% in weight. Condensing plants which have condensers at the outlet of the turbine and conventional cooling towers, the average consume is only 6–10 kg of steam per kWh generated, but the gas content of the steam must be less than 15%. Typical size of these steam turbine units ranges at the capacity of 20-120 MW_e. However, water-dominated fields are much more common than vapour producing fields, but they are suitable for electricity production only if they can provide hot water at temperatures above 85℃. Electricity can be produce d from hot water with binary cycle plants, which operate with a secondary, low boiling-point working fluid in a Rankine cycle. Typically the unit size is 1-3 MW_e. The working fluid is vaporized by the geothermal heat in the vaporizer. The exhaust vapour is subsequently condensed in a water cooled condenser or in an air cooler and is recycled to the vaporizer by the motive fluid cycle pump. According to Barbier (2002), this binary power plant technology is the most cost-effective and reliable way to convert large amounts of low temperature geothermal resources into electricity and it is now well known that large low-temperature reservoirs exist at accessible depths almost anywhere in the world. [1]

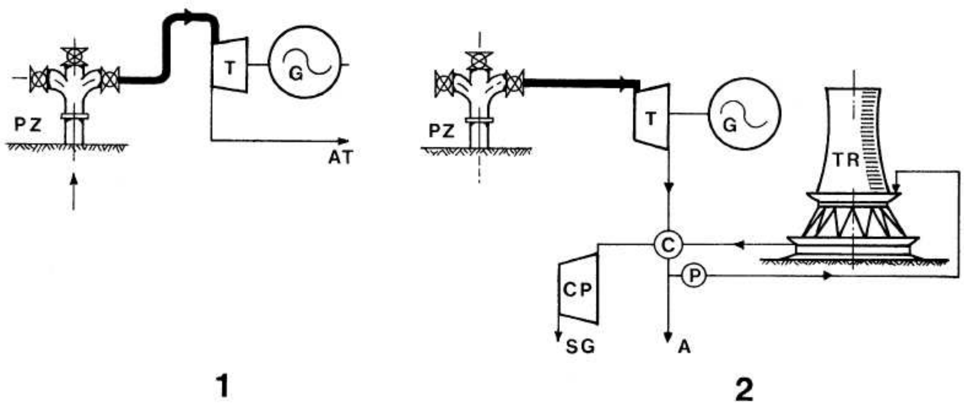


Figure 19. Geothermal cycles for generation of electricity. 1) Direct-intake exhausting-to-atmosphere turbine. 2) Direct-intake condensation turbine and cooling tower. PZ, geothermal well; T, turbine; G, generator; AT, exhaust to atmosphere; CP, compressor-extractor of non-condensible gases contained in the geothermal fluid; SG, gas discharge; C, condenser; P, pump; A, water discharge; TR, cooling tower. [1]

The total costs of geothermal power generation consist of the costs of bringing the useable geothermal fluids to the surface and returning the cooled fluids to the reservoir. The thermodynamic conditions (such as pressure, temperature and flow rate) influence the capital costs of the power plant. In 2002, the total costs of realizing a geothermal power plant varied on average from 800 to 3,000 US$ per installed kW. For instance, investment cost for a 40 MW geothermal power plant field was 51 million US$ with a range of 1,062 - 1,692 US$ per installed kW. The cost of drilling may be as high as 50% of the total cost of a project. To finance the high investment costs, geothermal reservoirs must be capable of sustaining the expected amount of energy production for the lifetime of the geothermal installations, which may be about 30 years. [1]

The emissions from the geothermal power plant are generally low compared to fossil-fired generation. Emissions are dependent on the variations in the gas content of the geothermal fluids and the design features of the geothermal power process. According to Barbier (2002), steam from major geothermal fields has a content of non-condensible gases (CO_2, H_2S, NH_3, CH_4, N_2 and H_2) that ranges from 1.0 to 50 g/kg of steam. CO_2 emissions are in the range of 0.01–0.4 kg/kWh. Hydrogen sulfide (H_2S) emissions generally range between 0.5 and 6.8 g/kWh. In addition, it may contain ammonia (NH_3), traces of mercury (Hg), boron vapors (B), hydrocarbons such as methane (CH_4) and radon (Rn). On the other hand, Kitz (2000) [2] states that other emissions are in general zero or negligible, but CO_2 emissions can reach 408 kg per MWh. However, binary plants, in which the geothermal fluid is passed through a heat exchanger and reinjected without exposure to the atmosphere, will not discharge either gas or fluid to the environment during normal operation.[1]

3. Heat Generation

3.1. Boiler

A boiler is a closed vessel in which water or other fluid is heated. The heated or vaporized fluid exits the boiler for use in various processes or heating applications.

The source of heating is a flame that could be fed with solid, liquid or gaseous fuel. This device is called “burner” and has different shape according to the kind of fuel utilised.

A boiler can produce hot water (about 80°-90℃) or water steam at a temperature level above 100℃ up to 500℃, depending on the purpose of the steam production (heating or power generation.

Usually hot water/steam production is for heating/power generation or sanitary purpose.

There are two main boiler types, depending where the water flows, i.e. internally or externally the pipes:

- Fire-tube boiler:

The water partially fills a boiler barrel with a small volume left above to accommodate the steam (steam space). The heat source is inside a furnace or firebox that has to be kept permanently surrounded by the water in order to maintain the temperature of the heating surface just below boiling point. The furnace can be situated at one end of a fire-tube which lengthens the path of the hot gases, thus increasing the heating surface which can be further increased by making the gases reverse direction through a second parallel tube or a bundle of multiple tubes (two-pass or return flue boiler); alternatively the gases may be taken along the sides and then beneath the boiler through flues (3-pass boiler). Fire-tube boilers usually have a comparatively low rate of steam production, but high steam storage capacity. Fire-tube boilers mostly burn solid fuels, but are readily adaptable to those of the liquid or gas variety.

- Water-tube boiler.

In this type, the water tubes are arranged inside a furnace in a number of possible configurations: often the water tubes connect large drums, the lower ones containing water and the upper ones, steam and water; in other cases, such as a mono tube boiler, water is circulated by a pump through a succession of coils. This type generally gives high steam production rates, but less storage capacity than the above. Water tube boilers can be designed to exploit any heat source and are generally preferred in high pressure applications since the high pressure water/steam is contained within small diameter pipes which can withstand the pressure with a thinner wall. For some applications a steam reservoir could avoid start and stop of this “instantaneous” steam generator. Sometimes this kind of boiler is preferred because up to 1000 kg/h of steam production, internal steam volumes are low and it is possible to avoid a dedicated operator of the boiler (e.g. for Italian laws)

Other kind of steam generators are:

- Superheated steam boilers

These boilers produce steam to be used at saturation temperature, also called saturated steam. Superheated steam boilers vaporize the water and then further heat the steam in a super heater. This provides steam at much higher temperature, but can decrease the overall thermal efficiency of the steam generating plant because the higher steam temperature requires a higher flue gas exhaust temperature.

- Supercritical steam generators

Supercritical steam generators are frequently used for the production of electric power. They operate at "supercritical pressure". Supercritical steam generator works at such a high pressure (over 220.6 barg, water critical point) that water is no more a “vapour” and it behaves like a gas. Practically above critical point, there is no generation of steam bubbles within the water, because there is not double-phase water/vapour, only uncondensable water gas. Steam passes below the critical point as it does work in the high pressure turbine and enters the generator's condenser. This is more efficient, resulting in slightly less fuel use.

Equipments utilised to produce hot water/steam are:

- Hydronic boilers

Hydronic boilers can produce heat for residential and industrial purposes. They are the typical power plant for central heating systems fitted to houses in northern Europe, in combination with domestic hot water production. The hydronic boiler operates by way of heating water/fluid to a temperature (or sometimes in the case of single pipe systems, until it boils and turns to steam) and circulating that fluid throughout the home typically by way of radiators, baseboard heaters or through the floors. Any kind of fuel can heat the boiler, but preferred fuel can be natural gas (where piping gas network is available) or fuel oil or wood The heating fluid (normally water) circulates in a closed loop by means of circulation pumps and it reached radiators releasing heat to the internal environment. Some new systems are fitted with condensing boilers for greater efficiency. These systems operate at lower temperature level than typical hydronic boilers and they “condense” water vapor of the flue gas, utilizing the latent heat of the condensing water. Flue gas contains carbon dioxide that, bounded with water, forms carbonic acid which may corrodes the flue and fireside boiler heating surfaces if these surfaces are not properly build with appropriate materials (i.e. stainless steel). Carbonic acid is drained out to waste water collection system. Condensing boilers are still less common than other types of hydronic boilers because they are more expensive.

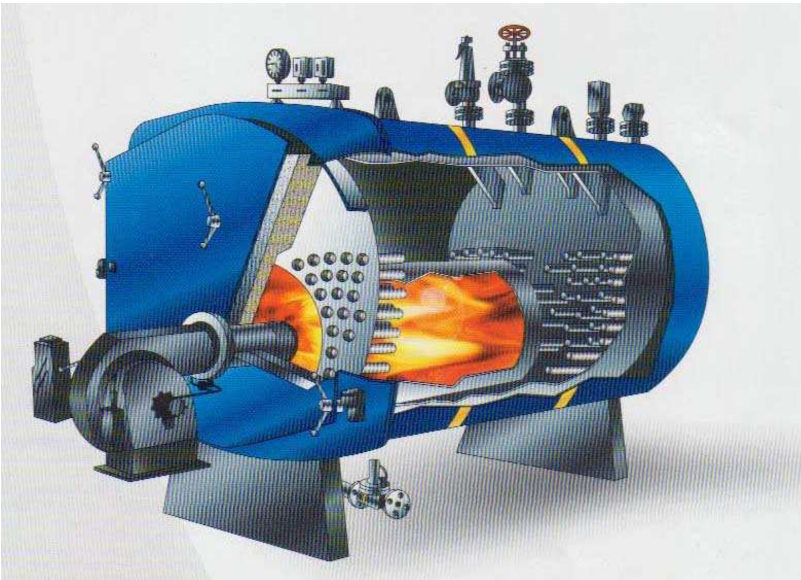


Figure 20. Boiler (www.watertubeboiler.org)

The heat delivered by a boiler is theoretically the chemical energy entering the system through the fuel minus the heat released in the environment through the chimney. Usually PER for this kind of boiler is about 85%.

The heat delivered by a condensing boiler is theoretically the chemical energy entering the system through the fuel minus the heat released in the environment through the chimney, adding the latent condensing heat of the vapour of water that is condensing prior to be released in the environment, thus increasing the PER of the boiler up to 95%.

The primary energy ratio (PER) is simply the ratio between useful energy output divided by the necessary energy input. This ratio is a measure of the overall efficiency of a heating system, taking into account the energy losses related to the generation of electricity. A higher PER corresponds to a more energy-efficient system.

Boilers deliver heat through circulation pumps, utilising sometimes accumulation tanks.

Boilers can range from few kW (th) for single dwelling unit for heating or sanitary/heating, up to large boilers for power generations, passing through centralised heating for buildings or districts.

Boilers have an average price lower than 50 €/kW th.

The modelling of a single boiler is defined by the following equations:

- Requested Heat [MJ]: the heat flow requested by the heating supply circuit

$$H_{requested} = H_{supply} - H_{return} \quad (3.1.1)$$

- Supply temperature [^{o}C]. Defined according to the needs of the user

$$T_{supply} = H\ supply / Q * cp \quad (3.1.2)$$

where: Q = water flow rate [kg / h]
cp = specific heat of water [kJ / kg K]

- Return temperature[ºC]. Defined by the heating delivered through the heating circuit

$$T_{return} = T\ supply - H\ requested / Q * cp \quad (3.1.3)$$

- PER (Primary Energy Rate) [-]:Ratio between the output heat and the chemical heat (fuel) consumed by the system.

$$PER = H\ requested / (Q * Fuel\ Energy) \quad (3.1.4)$$

where: Fuel Energy = Entalpy of Fuel [MJ / kg] or [Nm3/h]

- Buffer capacity [J]. Calculated from difference between supply and return temperatures, heat capacity of the used storage material, density and buffer size.

$$BCmax = cp_{water} * \rho_{water} * V * \Delta t \quad (3.1.5)$$

- SoC (state of Charge) [-] of the buffer. Calculated from the actual buffer temperature, supply- and return temperatures, being constant the T supply and T return Let “BC” be the actual Buffer Charge (i.e. SoC of the buffer)

$$SoC = BCmax - (Q*cp*T\ supply\ *time) \quad (3.1.6)$$

where: time = timeframe within water is supplied at T supply

- Electrical power [W]. Electricity consumed by the boiler. Electrical energy is consumed to run instruments and pumps, not directly involved in the production of heat nor conversion of electrical energy to heat.

3.2. “Electric Resistance systems”

Electric resistance systems are utilised mainly to convert (nearly 100%) electric energy to heat.
Considering that most electricity is produced from oil, gas, or coal generators that convert only about 30-35% of the fuel's energy into electricity and transmission losses, heat generated by electric is often more expensive than heat produces using combustion devices, fuelled by natural gas or liquid combustibles such as propane or oil.
On the other hand, electric heat installation is cheaper and easier to install than heating system with gas or other combustibles.
There are a lot of types of electric resistance heaters, mainly resistance heater that heat the air or heaters that heat water. Air and water are energy means that allow to utilise the heat generated.

- Air heaters:

Air can be heated in a centralised electric furnace and delivered into rooms through air ducts or air can be heated locally in the room by means of static resistances radiators or radiators with fan ventilation.

– Water heaters:

Water heaters heat water for sanitary purposes mainly. Hot water can be stored in insulated tanks prior to be utilised.
Hot water storage can be utilised as a thermal reservoir in case of electrical energy is paid with different rates according to the period of consumption, i.e. during “peaks” the electrical company increases the price to customers, then they can produce hot water during off-peak periods, store the hot water and save money. A drawback is that some losses can occur due to heat transmission through insulation and through distribution pipe lines.

As a general rule, the electric resistance heater is suitable for installation close to the point of use, since installation can be easier that other heating systems with distribution piping. In this way it is possible to heat where and when is needed, i.e. when people is present at office or at home.

The primary energy ratio (PER) is simply the ratio between useful energy output divided by the necessary energy input. This ratio is a measure of the overall efficiency of a heating system, taking into account the energy losses related to the generation of electricity. A higher PER corresponds to a more energy-efficient system.

The heat delivered by a electric resistance system is theoretically the electrical energy entering the system (consumption of electrical energy), thus the conversion rate is about 100%, not considering the electric power production.
We shall consider for the PER that in Europe electrical generation rate is about 38-40% of the overall energy conversion, thus lowering the conversion rate starting from primary energy.

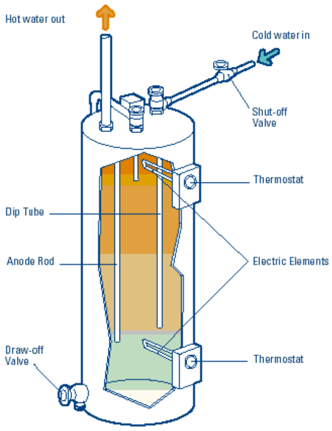


Figure 21. Water heater
(http://oee.nrcan.gc.ca)

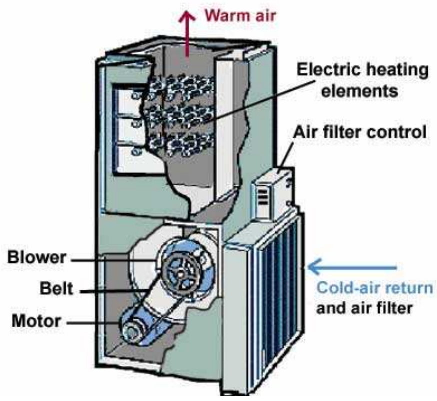


Figure 22. Air heater
(http://repairsncares.com/repairsncares/hotwaterheaters)

Electric resistance system can range from few kW (th) for single dwelling unit for heating or sanitary/heating, up to large furnaces for HVAC air heating with electrical elements.

Electrical heaters have an average price of around 100 €/kW

The modelling of a single electric resistance system is defined by the following equations:
The below equation refers to a system that utilises water to transfer the generated heat to the circuit. Instead of utilising the water it is possible to utilise the air. Then the specific heat shall be referred to air, not to water (see equation 1 and 2).

For equation 4 and 5 the cp remains referred to water, since it is relevant to water storage systems.

– Requested Heat [W]: the heat flow requested by the heating supply circuit

$$H_{requested} = H_{supply} - H_{return} \qquad (3.2.1)$$

– Supply temperature [^oC]. Defined according to the needs of the user

$$T_{supply} = H_{supply} / Q * cp \qquad (3.2.2)$$

where:
Q = water flow rate [kg / h]
cp = specific heat of water [kJ / kg K]
H supply: Energy flow (power) [W]

- Return temperature[ºC]. Defined by the heating delivered through the heating circuit

$$T_{return} = T_{supply} – H_{requested} / Q * cp \qquad (3.2.3)$$

- PER (Primary Energy Rate) [-]:Ratio between the output heat and the chemical heat (fuel) consumed by the system.

$$PER = H_{requested} / H_{fuel} \qquad (3.2.4)$$

where:
P e (Electrical power)= [W e]
H_{fuel} (chemical energy from fuel) [J]

$$\text{if: } H_{fuel} = P_e / 0.40 \qquad (3.2.5)$$

(being 0.40 average Europe conversion rate for power production), then:

$$PER = (H_{requested} / P_e) * 0.40 \qquad (3.2.6)$$

- Buffer capacity [J]. Calculated from difference between supply and return temperatures, heat capacity of the used storage material, density and buffer size.

$$BC_{max} = cp_{water} * \rho_{water} * V * \delta T \qquad (3.2.7)$$

- SoC (state of Charge) [-] of the buffer. Calculated from the actual buffer temperature, supply- and return temperatures, being constant the T supply and T return Let "BC" be the actual Buffer Charge (i.e. SoC of the buffer)

$$SoC = BC_{max} – (Q*cp*T_{supply} *time) \qquad (3.2.8)$$

where:
time = timeframe within water is supplied at T supply

3.3. Solar Thermal

<u>SOLAR COLLECTORS</u>

Collector performance

A solar collector is a device that converts solar irradiation to thermal energy. With increasing temperatures, the heat losses from a solar thermal collector increase and the efficiency is therefore reduced, depending on the level of insulation of the collector. Several types of solar thermal collectors are marketed, with very different levels of insulation. For low temperatures, unglazed collectors are sold such as swimming pool collectors. For high temperatures, concentrating collectors, evacuated tube collectors and double glazed collectors are available, while the highest temperatures are reached with central receiver systems. For tap water heating, which is the largest part of the collector market, mostly single-glazed flat plate collectors are used, but also evacuated tube collectors (especially in China).

Examples of the different collector types are shown below:

Figure 23. Swimming pool collector (sundisc), Evacuated tube collector (Soltech Int. Co), Flat plate collector (21st century solar).

Figure 24. (a) Solar trough collector, (b) central receiver collector

The efficiency of a solar collector is normally expressed in the collector efficiency curve. The collector power per unit area (in W/m2) is expressed as:

$$\frac{P_{coll}}{A_{coll}} = \eta_0 I_{solar} - k_1 \left(T_f - T_a\right) - k_2 \left(T_f - T_a\right)^2 \qquad (3.3.1)$$

As can be seen from this formula, the higher the temperature is, the higher the losses from the collector become. If the collector reaches its stagnation temperature, all heat is lost to the ambient and the efficiency is zero. For unglazed collectors, the wind speed has a large effect on the losses from the collector, and wind loss coefficients are included in the efficiency curve. A number of collector efficiency curves for different flat-plate and evacuated tube collectors are shown in Figure 25. The efficiency is plotted versus reduced temperature, which is defined as:

$$T_{red} = \frac{\left(T_f - T_a\right)}{I_{solar}} \qquad (3.3.2)$$

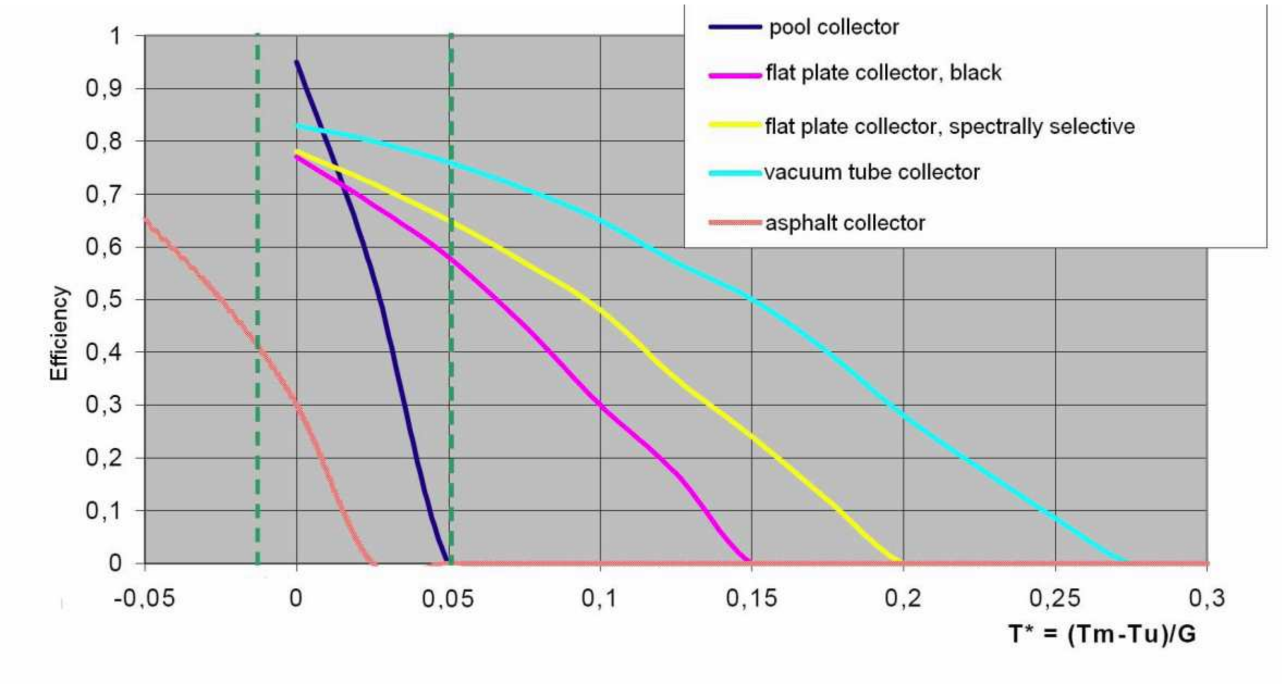


Figure 25. Collector efficiency curves (VITO, H. Hoes).

For flat-plate glazed collectors, 0 is about 0.75-0.8, while k1 is about 3.5-4 W/m2K and k2 about 0.0014 W/m2K2. For pool collectors and unglazed collectors, efficiency curves tend to be very steep, especially at high wind speeds. Typical values for k1 are in the range of 0.91-0.82 and for k2 are in the range of 10-24 W/m2K, for wind speeds of 0-3 m/s.

For concentrating collectors, the loss coefficient is relatively small, since the loss area (determined by the absorber) is much smaller than the collection area (determined by the mirror). For concentrating collectors, the loss coefficient is in the order of 3-2 W/m2K for low-concentrating collectors with singe cover, and 1 W/m2K can be reached if a double glass cover is used. For highly concentrating collectors, loss coefficients in the order of 0.15 W/m2K can be reached. However, the higher the concentration factor, the smaller the angle of acceptance of the solar radiation. Therefore, for concentrating collectors, sun tracking becomes important.

Collector system performance

The yield of a solar collector system is related to the solar collector module area, but also to other aspects, such as the thermal energy demand. If the collector area is increased to cover a larger fraction of the heat demand, the average temperature at which the solar collector system operates will increase, reducing the efficiency of the collectors. If the solar supply is higher than the thermal demand over a long time, the solar storage (hot water tank) will become full and the temperature control will switch off the pump to prevent boiling in the solar storage vessel. In that case the collectors under full sun will heat up to their stagnation temperature, which for evacuated tube collectors can be as high as 250℃, and lose their heat by heat loss to the ambient. Furthermore, the system performance is affected by heat loss from the pipes and the storage vessel.

The best way to determine the annual performance of a collector system, is by carrying out a dynamic calculation of the collector yield over an entire year (calculating storage temperatures for every hour of the year), and from the results determine the overall annual collector yield.

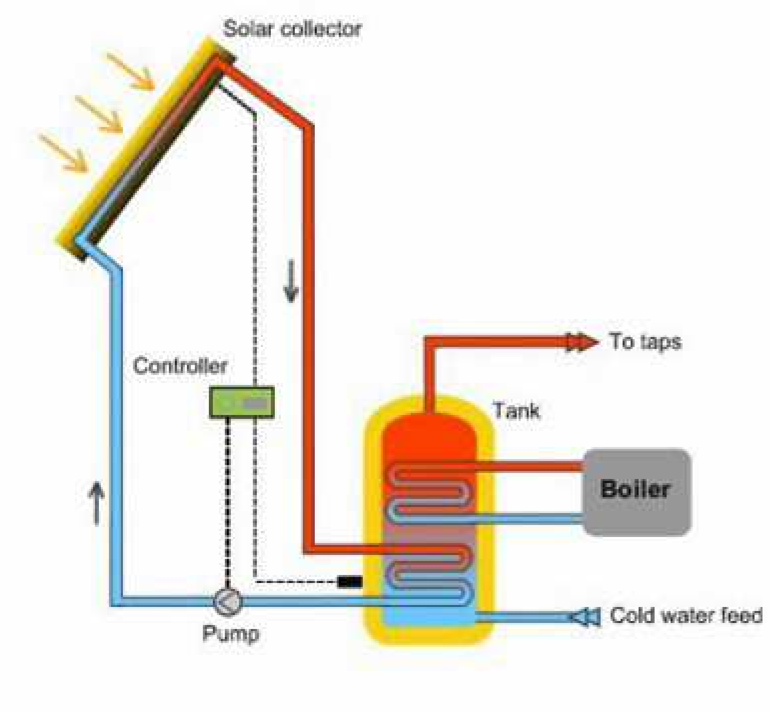


Figure 25. Solar water heating system (www.daviddarling.info).

Key performance indicators:

- Power range (kW): 0.8-0 kW/m2
- coefficient of performance (COP), n/a
- primary energy ratio (PER)(if possible): n/a
- Primary energy used: 25W + 2W/m2 x Acollector (pump power) .
- Cost of the equipment (€/kW): 200-1000 euro/kW. (In general, the larger the system, the lower the costs per kW).

ROAD THERMAL COLLECTORS

A road thermal collector is basically a road with pipes beneath it. Fluid running through them will extract heat from the upper part of the road, which is heated by solar radiation. The thermal energy potential of a road thermal collector is lower than that of a normal solar hot water system and the quality of the energy is also lower but there are many advantages of the use of this kind of systems.

Asphalt pavements can heat up to 60-70º C during solar irradiation and the available area of asphalt is so enormous that the energy potential appears to be huge. This heat can be used in many ways. Usually this energy is stored over seasons by means of aquifers, borehole heat exchangers, energy piles, etc. Besides the energy storage, another advantage of the use of a road thermal collector is also found in the maintenance of the road. The maximum temperature of the road (in summer) can be damped so that the chance of formation of ruts is reduced. In winter time, it is possible to avoid slippery roads by damping the minimum asphalt temperature.

Although there are additional advantages of using road thermal collectors, interest is mainly focussed on the energy potential and the application of this technology in order to reduce energy consumption in the built environment.

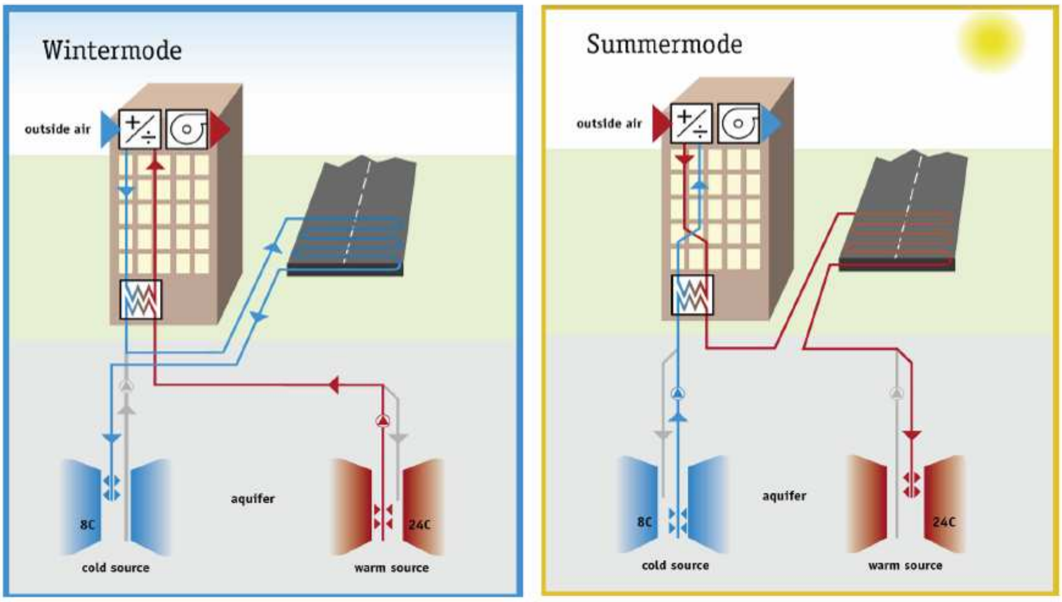


Figure 26. Road thermal collector diagram

Inside the ground, the heat is transferred through conduction in all three dimensions. A simplified model is going to be presented here, considering that the road solar collector is much longer than it is wide, a 2D model would be suitable to take into consideration the main driving forces of the conduction heat transfer, for which the main equation is:

$$\rho c \frac{\partial T}{\partial t} = k\left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right] \quad (3.3.3)$$

At the surface boundary, there are some heat fluxes that have to be taken into account in order to implement the domain boundary conditions:

- the convection with the ambient air.
- the incident solar radiation.
- heat emitted to the sky by means of long wave radiation.

To be more complete, the effect of the rain on the surface temperature should be taken into account, however it is neglected in order to simplify the model.

The boundary condition at the surface is going to be set by using the Sol-Air temperature. Sol-Air temperature is the outdoor air temperature that, in the absence of all radiation changes gives the same rate of heat entry into the surface as would the combination of incident solar radiation, radiant energy exchange with the sky and other outdoor surroundings, and convective heat exchanger with outdoor air.

Heat Flux into Exterior Sunlit Surfaces. The heat balance at a sunlit surface gives the heat flux into the surface q/A as

$$\frac{q}{A} = \alpha E_t + h_o(t_o - t_s) - \epsilon \Delta R \quad (3.3.4)$$

α	=	absorptance of surface for solar radiation
E_t	=	total solar radiation incident on surface, W/m2
h_o	=	coefficient of heat transfer by long-wave radiation and convection at outer surface, W/(m2K)
t_o	=	outdoor air temperature, ºC
t_s	=	surface temperature, ºC
ϵ	=	hemispherical emittance of surface
ΔR	=	difference between long-wave radiation incident on surface from sky and surroundings and radiation emitted by blackbody at outdoor air temperature,W/m2.

Assuming the rate of heat transfer can be expressed in terms of the sol-air temperature t_sol,

$$\frac{q}{A} = h_o(t_{sol} - t_s) \quad (3.3.5)$$

and from the last equations

$$t_{sol} = t_o + \frac{\propto E_t}{h_o} - \frac{\varepsilon \Delta R}{h_o} \quad (3.3.6)$$

For horizontal surfaces that receive long-wave radiation from the sky only (like the road thermal collector), an appropriate value of ΔR is about 63W/m2, so that if ε=1 and h_o=17 W/m2K, the long-wave correction term is about 4 (Bliss 1961).

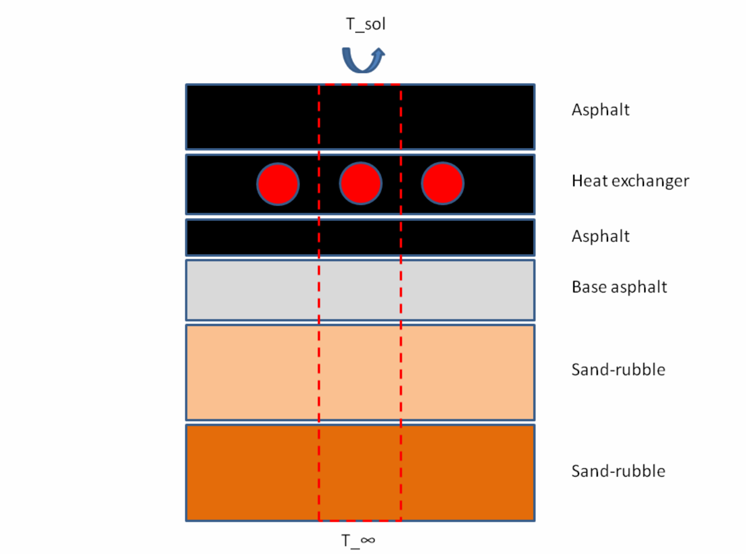


Figure 27. Simplified model of the road thermal collector

The characteristic variation time of the air temperature and solar incident energy is one year. For the time τ, the temperature will have an influence (through conduction) on the ground inside a length that is smaller than the following

$$L_{car} = 2\sqrt{\alpha\tau} \quad (3.3.7)$$

The ground far away from the edges of the portion of the road which is modelled has very little influence on the temperatures below the road. This region is called farfield and is used only to set the boundary conditions. The temperature there T (Z=L, t) can be calculated using the Kasuda equation.

$$T = T_{mean} - T_{amp} * exp\left(-Z\sqrt{\frac{\pi}{365 * \alpha}}\right) * \cos\left(\frac{2\pi}{365} * \left[t_{year} - t_{shift} - \frac{Z}{2} * \sqrt{\frac{365}{\pi * \alpha}}\right]\right) \quad (3.3.8)$$

T = Temperature of soil (ºC)
T_mean = Mean surface temperature (average air temperature). The temperature of the ground at an infinite depth will be this temperature (ºC)
T_ amp = Amplitude of surface temperature (the maximum surface temperature will be T_mean+T_amp and the minimum value will be T_mean-T_amp) (ºC)
Z = Depth below the surface (m)
α = Thermal diffusivity of the ground (m^2/day)
t_year = Current time (day)

t_{shift} = Day of the year of the minimum surface temperature (day)

A complete two-dimensional model can be solved taking into account the already described boundary conditions. Another option is defining a simplified domain containing just one pipe, considering symmetry boundary conditions at the right and left sides of the domain.

The thermal model of the real layout of a particular road solar collector will determine the thermal performance of the system. In general, it can be said that this kind of collectors will have a thermal performance lower than 30% (based on solar irradiation).

The cost of the equipment is about 25-40 €/m^2, just the asphalt collector, the price does not include neither the heat pump nor the heat storage system (aquifers, borehole heat exchangers, energy piles, etc.).

Considering a nominal solar irradiation of 1000 W/m^2 and a thermal performance of 25%, it would be necessary to have 4 m^2 in order to collect 1kW. That determines a price of 100-160 €/kW. It is important to notice that the maximum solar radiation on a horizontal surface is during summer when the heating requirements are low. It is also important to realize that this kind of system only provides low temperature heat, so the cost of the equipment cannot be compared directly to other types of thermal generation equipment.

3.4. Heat Pumps

Heat pump is a device able to transfer heat from one fluid at lower temperature to another at higher temperature. In order to transport heat from a heat source to a heat sink, external energy is needed to drive the heat pump. Theoretically, the total heat delivered by the heat pump is equal to the heat extracted from the heat source, plus the amount of drive energy supplied.

Figure 28. Heat Pump (www.lennox.com)

There are two main heat pump types:

- Vapour compression:

The main components in such a heat pump system are the compressor, the expansion valve and two heat exchangers referred to as evaporator and condenser. The components are connected to form a closed circuit. A volatile liquid, known as the working fluid or refrigerant, circulates through the four components. The compressor is usually driven by an electric motor and sometimes by a combustion engine.

- Gas absorption

Absorption heat pumps are thermally driven, which means that heat rather than mechanical energy is supplied to drive the cycle. Absorption heat pumps for space conditioning are often gas-fired, while industrial installations are usually driven by high-pressure steam or waste heat.

Absorption systems utilise the ability of liquids or salts to absorb the vapour of the working fluid. The most common working pairs for absorption systems are:

- water (working fluid) and lithium bromide (absorbent); and
- ammonia (working fluid) and water (absorbent).

In absorption systems, compression of the working fluid is achieved thermally in a solution circuit which consists of an absorber, a solution pump, a generator and an expansion valve. Low-pressure vapour from the evaporator is absorbed in the absorbent. This process generates heat. The solution is pumped to high pressure and then enters the generator, where the working fluid is boiled off with an external heat supply at a high temperature. The working fluid (vapour) is condensed in the condenser while the absorbent is returned to the absorber via the expansion valve.

The heat delivered by a heat pump is theoretically the sum of the heat extracted from the heat source and the energy needed to drive the cycle. The steady-state performance of an electric compression heat pump at a given set of temperature conditions is referred to as the coefficient of performance (COP).

For engine and thermally driven heat pumps the performance is indicated by the primary energy ratio (PER). The energy supplied is then the higher heating value (HHV) of the fuel supplied.

The COP or PER of a heat pump is closely related to the temperature lift, i.e. the difference between the temperature of the heat source and the output temperature of the heat pump. The COP of an ideal heat pump is determined solely by the condensation temperature and the temperature lift (condensation - evaporation temperature). The following figure is an example of how varies the COP with the temperature lift:

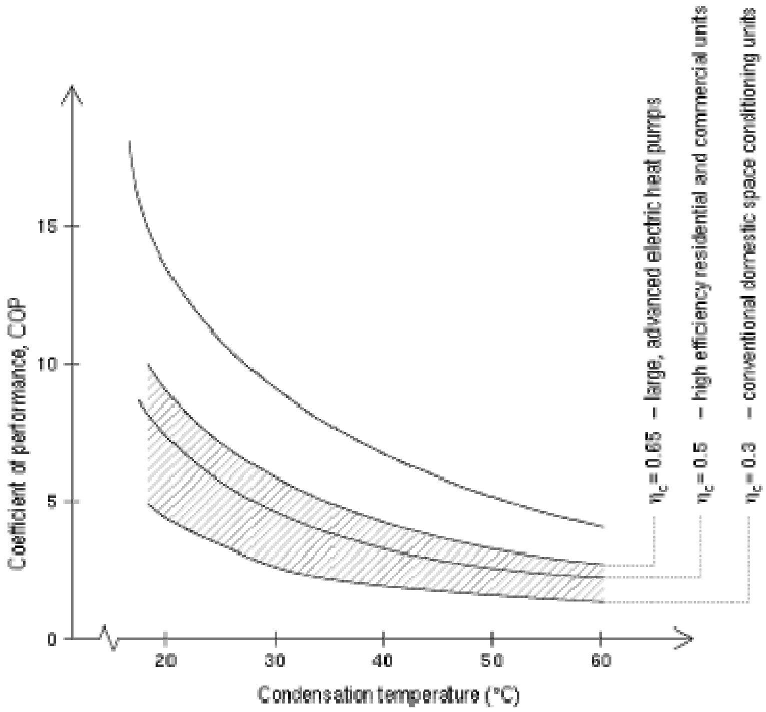


Figure 29. Variation of COP with the temperature lift

The typical COP/PER range for heat pumps with different drive energies at evaporation temperature of 0℃ and condensing temperature of 50℃ is shown in the following table.

Table 2. COP/PER of Heat pumps

Heat pump type	COP	PER
Electric (compression)	2.5 - 5.0	
Engine (compression)		0.8 – 2.0
Thermal (absorption)		1.0 – 1.8

Heat pumps have an average price of around 240 €/kW. There are heat pumps available between three power ranges:

- Low power: from some kilowatt to 50 kilowatts
- Medium power: from 50 kilowatts and 150 kilowatts
- High power: from 150 kilowatts to several Megawatts.

The modelling of a single heat pump is defined by the following equations:

- Supply temperature [^{o}C]. Defined by the heating curve.

$$T_{supply} = 40 - (T_{amb} + 10) / 1.5 \qquad (3.4.1)$$

- Return temperature[ºC]. Defined by the heating curve, in practice accomplished through control of the pump.

$$T_{return} = 30 - (T_{amb} + 10) / 1.5 \qquad (3.4.2)$$

- COP (Coefficient of performance) [-]. Ratio between the output heat and the electricity consumption of the system.

$$COP = 7.7 - 1.08 * T_{supply} \qquad (3.4.3)$$

- Buffer capacity [J]. Calculated from difference between supply and return temperatures, heat capacity of the used storage material, density and buffer size.

$$Cmax = C_{water} * \rho_{water} * V * \delta T \qquad (3.4.4)$$

- SoC (state of Charge) [-] of the buffer. Calculated from the actual buffer temperature, supply- and return temperatures.

$$SoC = 100 * Q/Cmax \qquad (3.4.5)$$

- Electrical power [W]. Electricity consumed by the heat pump. Calculated from the thermal output and actual COP.

$$ElectricalPower = HeatPower/ COP \qquad (3.4.6)$$

3.5. Geothermal

In general, geothermal energy generation utilizes the heat from the earth geological layers. Thermal energy can be used directly, or used for electricity production. It is good to note that geothermal energy generation can be considered as a renewable energy source only if the heat extraction rate does not exceed the reservoir replenishment rate. [1]

Highest energy resources locate mainly close to boundaries between lithospheric plates, where visible geothermal activity exists frequently (such as hot springs, fumaroles, steam vents, and geysers). According to Barbier (2002) the most important features of a good resource location are:

- a high temperature (for high power plant efficiency)
- a large quantity of stored heat (for resource longevity) and
- reinjection well sites available at a lower elevation than production (for disposal under gravity).

Geothermal energy generation is based on a reservoir, which is a sufficiently large body of permeable rocks at a depth accessible by drilling. The rock has to contain large amounts of fluids, water or steam, which carry the heat to the surface. Boiling is the most efficient mechanism due to the high heat transfer rates of vaporization and the high heat capacity of steam. The reservoir is bounded by cooler rocks hydraulically connected to the hot reservoir by fractures and fissures, which provide channels for rainwater to penetrate the reservoir. These cooler rocks crop out at the surface, where they represent the so-called recharge areas of the geothermal reservoir. Thermal waters or steam are, in fact, mainly rainwater that infiltrates into the recharge areas at the surface and proceeds to the depth of the reservoir, increasing the temperature while penetrating the hot rocks of the reservoir. Finally, the spent cooled fluid have to be disposed after utilizing its thermal energy; typically more than 95 % of it is reinjected into the reservoir as water, aiming to limit pressure losses and to replace at least part of the fluid extracted. As a result, the geothermal system is cooled with the same amount of energy than heat is utilized, excluding the natural heat inflow to geothermal system. However, the geothermal resource volume is large and hence, it allows the usage of the geothermal resource for many decades. This process is illustrated in figure 33. [1,2]

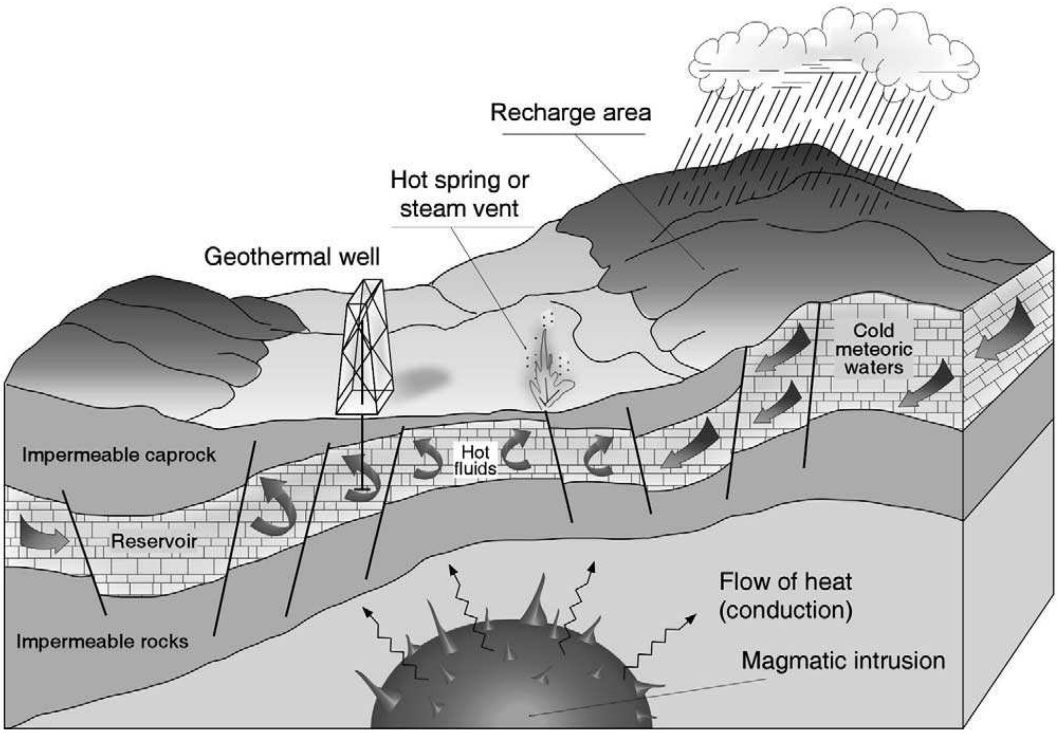


Figure 33. A geothermal steam field with its elements: a recharge area, an impermeable cover, a reservoir, and a heat source. [1]

Hot water from geothermal resources can be used for space heating, in which the ideal temperature of thermal waters for space heating is about 80 ℃. Large-scale district heating systems using geothermal water have been built in many countries, such as France, Russia, Georgia, China, Italy, and the USA. For example, in Island 90% of the total population live in houses that are heated by geothermal water. [1]

Heat pumps utilizing very low-temperature fluids (less than 50℃) can be utilized in the areas, which are traditionally classified as non-geothermal countries (such as France, Switzerland, Germany and Finland). Ground-coupled and groundwater heat pump installations use the ground or the groundwater as the heat source during the winter heating operations and as the heat sink during the summer cooling operation. [1]

In 2010 the most common way to utilize geothermal heat directly was geothermal heat pumps, which produced 68 percentage of total installed capacity. Other common solutions were space heating with district heating system (11 %) and bathing and swimming (14 %). The geothermal heat energy was also used for cooling and snow melting, industrial uses, agricultural drying and pond heating, as well as heating greenhouses. [3, 4]

4. Cogeneration

4.1. Organic Rankine Cycle (ORC)

The Organic Rankine Cycle (ORC) is similar to the cycle of a conventional steam turbine, except for the fluid that drives the turbine, which is a high molecular mass organic fluid. The selected working fluids allow exploiting efficiently low temperature heat sources to produce electricity in a wide range of power outputs (from few kW up to 2 MW electric power per unit).

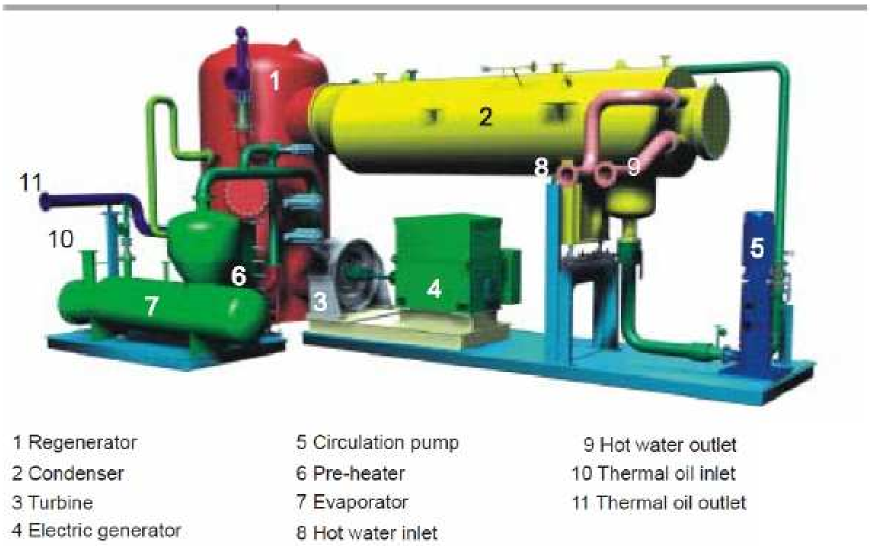


Figure 34. Organic Rankine Cycle scheme

The organic working fluid is vaporised by application of a heat source in the evaporator. The organic fluid vapour expands in the turbine and is then condensed using a flow of water in a shell-and-tube heat exchanger (alternatively, ambient air can be used for cooling). The condensate is pumped back to the evaporator thus closing the thermodynamic cycle. Heating and cooling sources are not directly in contact with the working fluid nor with the turbine. For high temperature applications (e.g. combined heat and power biomass-powered plants) high temperature thermal oil is used as a heat carrier and a regenerator is added, to further improve the cycle performance.

The following figure shows an example of Second Law efficiency (thermal efficiency relative to the Carnot efficiency) of an ORC as a function of heat source temperature for different working fluids.

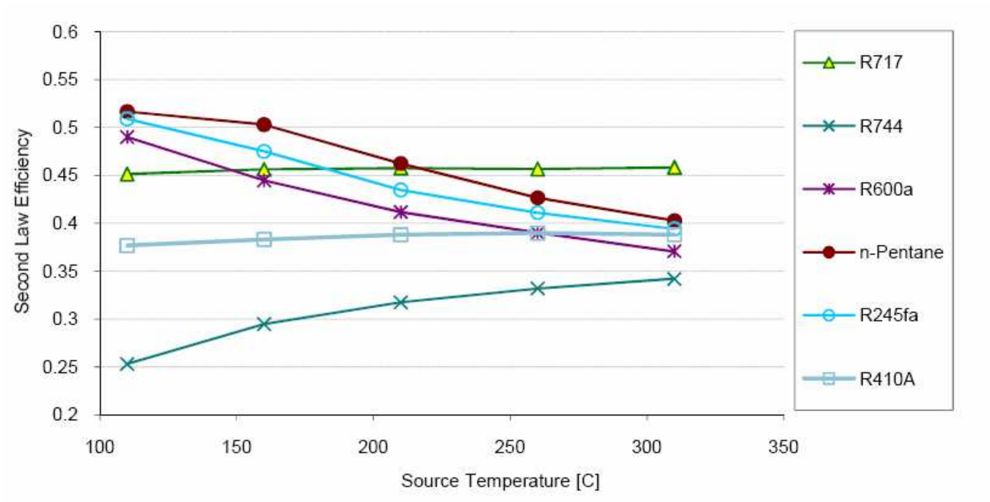


Figure 35. Second Law Efficiency vs. heat source temperature for different working fluids

Key technical benefits of ORC plants include:

- high cycle efficiency (<25%)
- very high turbine efficiency (up to 85 percent)
- low mechanical stress of the turbine, due to the low peripheral speed
- low RPM3 of the turbine allowing the direct drive of the electric generator without reduction gear
- no erosion of blades, due to the absence of moisture in the vapour nozzles
- long life
- no operator required

The system also has practical advantages, such as simple start-stop procedures, quiet operation, minimum maintenance requirements, good part load performance. Typical applications are:

- low enthalpy geothermal plants, up to 2 MW electric per unit
- combined Heat and Power (CHP) biomass powered plants, in the range 400 to 1500 kW electric
- heat recovery applications, in the range 400 to 1500 kW electric
- solar applications

ORC prices range from 1.000 €/kW$_e$ to 2.500 €/KW$_e$.

The modelling of the ORC unit is modelling by the following equations:

$$Q_{rec} = \eta_{rec} Q\_ \qquad (4.1.1)$$

where
Q - Heat available for the heat recovery system
η_{rec} - is the efficiency of the heat recovery system.

For the ORC cycle, values for the evaporator pressure and the condenser pressure are chosen along with isentropic efficiencies for the turbine and pump. The efficiency of the ORC system is given by

$$\eta_{ORC} = (w_t - w_p)/q_e \qquad (4.1.2)$$

where
w_p - specific work input required by the pump
w_t - specific work output from the turbine
q_e - specific heat transfer required in the evaporator.

The specific work input required by the pump, w_p, is

$$w_p = w_{p,s}/\eta_p = (h_{2,s} - h_1)/\eta_p = h_2 - h_1 \qquad (4.1.3)$$

where
$w_{p,s}$ - ideal (isentropic) specific work of the pump
ηp - isentropic efficiency of the pump
h_1 - enthalpy at the pump inlet of the saturated fluid
h_2,s - enthalpy of the working fluid at the exit of the pump for the ideal (isentropic) case
h_2 - enthalpy of the working fluid at the exit of the pump.

The specific work output from the turbine, wt is

$$w_t = w_{t,s}\eta_t = (h_3 - h_{4,s})\eta_t = h_3 - h_4 \qquad (4.1.4)$$

where
$w_{t,s}$ - ideal specific work of the turbine
η_t - turbine isentropic efficiency
$h_{4,s}$ - enthalpy of the working fluid at turbine outlet for the ideal (isentropic) case
h_4 - enthalpy of the working fluid at turbine outlet.

The specific heat transfer required in the evaporator is

$$q_e = h_3 - h_2 \qquad (4.1.5)$$

where
h_3 is the enthalpy at the evaporator exit.

While the specific values for work and heat transfer do not change and, therefore, the efficiency remains constant, the mass flow rate of the working fluid will adjust to absorb all of the available heat in the evaporator, such that

$$Q_e = m\, q_e \qquad (4.1.6)$$

where
m is the mass flow rate of the working fluid over an hour.

The net electric energy from the ORC is

$$E_{ORC} = Q_e \eta_{ORC} \eta_{gen} \qquad (4.1.7)$$

where η_{gen} is the electric generator efficiency.

4.2. CHP based on ICE

Combined heat and power system (CHP) system based on Internal Combustion Engine (ICE) has been developed since decades. FIAT started to study these systems in the ‘70s. An ICE working at constant rpm, is able to move an electric generator to produce electric power according to the need, within a working range. The system is quite flexible and can respond to the external energy request quite promptly.

During the working activity the ICE shall be cooled. The coolant exits from the ICE at a temperature level suitable to be utilised for heating and sanitary purposes, i.e. outlet temperature about 65°/ 70℃.

ICE can work with natural gas and many other combustible, liquid or gaseous (i.e. bio fuel, biogas, LNG, etc.).

Mainly CHP with ICE are utilised for:

- Industrial duty or district duty:

These equipments are utilised to feed electric power in case of emergency or to provide power in large construction sites where is not possible (or it is expensive) to provide electric power and hot water.

- Home duty:

It is possible to utilise CHP with ICE for small dwelling units where typically the needs of power are max 4 kWe (power peak) and the heat generated can be stores in an accumulation tank, to be use for heating or sanitary purposes.

The CHP is able to deliver electric power and thermal power. As an example, FIAT Tandem T20-A is able to supply 20 kWe and 47.5 kW th at nominal conditions.

Other systems can provide:

Table 4. Types of CHP with ICE

	Model	Manufacturer	Electric power [kWe]	Thermal power [kW th]
1	Ecopower	MARATHON	2	7
2	6 kW gas engine	Aisin Seiki Co. Ltd.	6	11
3	Freewatt®	American Honda Motor Co.	1.2	3.5 (@72℃)
4	XRGI 15G-TO	EC Power	15.2	30 (@78℃)
5	InVerde100	Tecogen	100	205 (@110℃)

CHP with ICE can range from one single dwelling unit (4 kWe) to over 100 kWe.

Figure 36. CHP with ICE (from Tecogen technical sheet)   Figure 37. CHP with ICE (from Freewatt O&M Manual)

CHP based on ICE has an average price of around 500 € / kWe installed.

The modelling of CHP with Ice is defined by the following equations:

$$\eta_{ep} = P_e / Q_f * \Delta H_f \qquad (4.2.1)$$

where:
P_e = Electric power (W e)
□H_f = enthalpy of fuel (MJ / kg)
Q_f = fuel flow rate (kg/h)

If we consider PER as the ratio between useful energy output divided by the necessary input, in this case we define a PERe, relevant to the electric power generated and made available to the grid.

$$PER_e = \eta_{ep} \qquad (4.2.2)$$

where:
PER_e = Primary Energy Ratio (Electric power)

Similarly we can define PER th Primary Energy ration for generated heat, made available to thermal users circuit.

We define H requested [J] as the heat released in the circuit to users, including the distribution losses:

$$H_{requested} = H_{supply} - H_{return} \qquad (4.2.3)$$

Where:

$$H_{supply} = Q_{supply} * cp * T_{supply} \qquad (4.2.4)$$
$$H_{return} = Q_{return} * cp * T_{return} \qquad (4.2.5)$$

Being:

$$Q_{supply} = Q_{return} = Q \text{ (same closed circuit)} \qquad (4.2.6)$$

Then:

$$PER_{th} = H_{requested} / Q_f * \Delta H_f = Q * cp * \Delta T / Q_f * \Delta H_f \qquad (4.2.7)$$

$$PER = PER_e + PER_{th} = (P+Q*cp*\Delta T) / Q_f * \Delta H_f \qquad (4.2.8)$$

If H requested is the heat released by CHP system, taking into account the distribution losses, the heat utilised by users is:

$$H_{users} = H_{requested} * 0.91 \qquad (4.2.9)$$

where:
0.91 is distribution losses rate

Information of a real case study can be found in the document "Energy performance evaluation of a 5,5kW micro-cogeneration unit" (Authors: Koen Allaerts, Thomas Nuytten, Johan Van Bael) which is available in the webpage.

4.3. CHP based on External Combustion Engines (Steam)

The CHP system based on External combustion Engine is a system where the working fluid is heated by a heat source (as combustion, solar thermal or nuclear reaction) and flows in the engine or in the external part of it.
The fluid expands in the engine and through a mechanism this expansion is transformed in motion and work. Then this fluid can be cooled, compressed and re-heated externally (closed loop) or discharged to environment.

Heat sources can be various, as previously described. Strictly "combustion" refers to the reaction between a fuel and an oxidiser (usually oxygen contained in the air), that heat the fluid to a temperature level and pressure able to expand and move the engine.
We focus on a External combustion engine that utilise steam as a working fluid.
This "steam engine" works according to a thermodynamic cycle called Rankine Cycle. Liquid water is pumped in a boiler, changes phase from liquid to vapour, sometimes is overheated over the critical point, then the steam is expanded in a steam turbine, transforming the expansion into mechanical (and then electric) energy. The low pressure steam is then condensed into liquid in a low pressure condenser (usually 0.05 bar a and 35°C). Then the liquid water is pump ed again in the boiler and the cycle restarts.

There are several configuration and optimization of this system with partial injection of steam, or possibility of cogeneration, without condensing down to +35°C but only 90°C in order to use this hot water. In some c ases water is heated in a heat recovery exchanger in the external combustion part, where fumes are cooled down prior to be discharged in the environment.

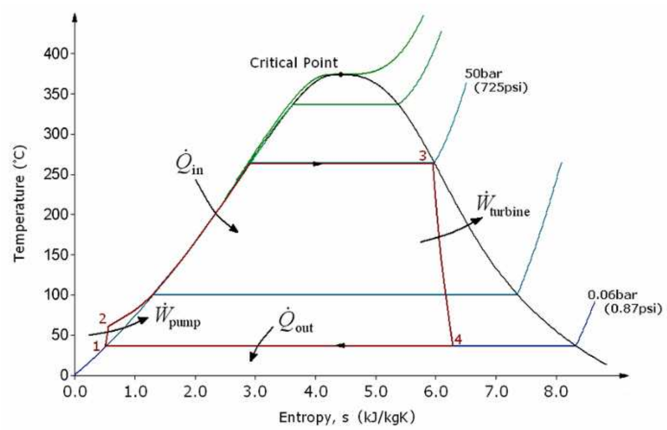


Figure 38. Rankine Cycle

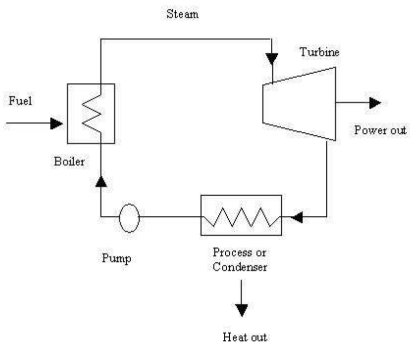


Figure 39. System configuration

Fields of application of CHP based on ECE (based on steam) are mainly:

- Production of Steam:

CHP systems based on Steam turbine are primarily used in industrial processes where solid or waste fuels are available for boiler use. In CHP applications, steam is extracted from the steam turbine and used directly in a process or for district heating, or it can be converted to other forms of thermal energy including hot water or chilled water. The turbine may drive an electric generator or equipment such as boiler feed water pumps, process pumps, air compressors and refrigeration chillers. Turbines as industrial drivers are, in most cases, a single casing machine, either single stage or multistage, condensing or non-condensing depending on steam conditions and the value of the steam. Steam turbines can operate at a single speed to drive an electric generator or operate over a speed range to drive a refrigeration compressor. For "non-condensing applications", steam is exhausted from the turbine at a pressure and temperature sufficient for the CHP heating application.

For "extraction turbine" application the turbine has opening(s) in its casing for extraction of a portion of the steam at some intermediate pressure. The extracted steam may be use for process purposes in a CHP facility, or for feed water heating as is the case in most utility power plants. The remaining steam is condensed and reused.

– Production of Power:

The primary type of turbine used for central power generation is the "condensing turbine". These power-only utility turbines exhaust directly to condensers that keep vacuum conditions at the discharge of the turbine. The heat exchanger (usually a Shell&Tube condenser) cooled with water (fed from several cooling sources, i.e cooling tower or fresh water) condenses the steam into (liquid) water. The condenser vacuum is achieved by cooling with the near ambient-temperature water, thus causing condensation of the steam turbine exhaust in the condenser. A small amount of air can leak into the system because the condenser operates below atmospheric pressure, therefore, a relatively small vacuum pump is used to remove non-condensable gases from the condenser.

The condensing turbine process results in maximum power and electrical generation efficiency. The power output of condensing turbines is very sensitive to ambient conditions, since internal condenser pressure is thermodynamically bound to environmental water temperature.

The capacity of steam turbines can range from 50 kW to several hundred MWs for large utility power plants. Steam turbines are widely used for CHP applications in the U.S. and Europe.

CHP based on ECE (Steam) has an average price of more than 1400 € / kWe installed.
The cost of the system includes boiler, fuel handling, storage and preparation system, stack gas cleanup and pollution controls, steam turbine generator, field construction and plant engineering.

Steam turbine thermodynamic efficiency is a measure of how efficiently the turbine extracts power from the steam itself and is useful in identifying the conditions of the steam as it exhausts from the turbine and in comparing the performance of various steam turbines.

Multistage (moderate to high pressure ratio) steam turbines have thermodynamic efficiencies that vary from 65% for very small (under 1,000 kW) units to over 90% for large industrial and utility sized units.
Small, single stage steam turbines can have efficiencies as low as 50%.

Steam turbine CHP systems are generally characterized by very low power to heat ratios, typically in the 0.05 to 0.2 range. This is because electricity is a by-product of heat generation, with the system optimized for steam production. Hence, while steam turbine CHP system electrical efficiency may seem very low, it is because the primary objective is to produce large amounts of steam.

Electrical efficiency can be defined as:

$$\text{Electrical Efficiency} = \frac{\text{(Steam turbine electric power output)}}{\text{(Total fuel into boiler - (steam to process / boiler efficiency))}} \quad (4.3.1)$$

The effective electrical efficiency (Net power and steam generated divided by total fuel input) of steam turbine systems is generally high, because almost all the energy difference between the high pressure boiler output and the lower pressure turbine output is converted to electricity.
This means that total CHP system efficiencies are generally very high and approach the boiler efficiency level. Steam boiler efficiencies range from 70 to 85 % HHV.

If we consider PER as the ratio between useful energy output together with thermal energy divided by the fuel energy input, then:

$$PER = \frac{P_e + Q_s * \Delta H_s + Q_w * cp * \Delta T}{Q_f * \Delta H_f} \quad (4.3.2)$$

where:
P_e = Electric power (W e)
ΔH_f = enthalpy of fuel (MJ / kg)
ΔH_s = enthalpy of steam (MJ/kg)
Q_f = fuel flow rate (kg/h)

Q_s = steam flow rate (kg/h)
Q_w = water flow rate (kg/h)

The steam to process is the steam made available for process purposes:

$$\text{Steam power} = (Q_s{*}\Delta H_s) \qquad (4.3.3)$$

Hot water generated is represented by:

$$\text{Hot water power} = Q_w{*}cp{*}\Delta T \qquad (4.3.4)$$

The modelling of CHP with ECE is quite complicated and cannot be described simply with few equations. Many components interacting each other are involved, influencing the behaviour of the CHP system, also due to the process settings (temperature, pressure, recycle rate, “extraction steam”) and the steam flow rate needed for process purposes.

4.4. CHP based on External Combustion Engines (Stirling)

Stirling engine works with an external heat source that provides heat to an inert gas. The gas is contained in a cylinder and expands and condenses, moving piston(s). This movement is transmitted to a power generator. Excess heat is utilized for sanitary water or home heating purposes.

Stirling engines have begun to show market potential since the development of modern free-piston engines. The technology is used in residential cogeneration systems, with the ability to achieve high efficiency, flexibility with regard to fuel, low emissions and low noise levels.

Unlike internal combustion engines, the heat supply is from an external source, allowing the use of different energy sources including fossil fuels (oil or gas) and renewable energy such as solar or biomass. Although it is expected that the electrical efficiency can reach 50%, currently has only reached 40%, while the overall efficiency of a cogeneration system based on a Stirling engine is in the range 65-85%, with a power heat 1-10 kWe.

In details, the Stirling engine has a fixed working fluid that moves from an “upper heat source”, that increase the energy (pressure) of the working fluid. Energy is transformed into mechanical (and then electric) energy expanding the fluid with a piston. Working gas decrease its energy and finally it is “cooled” in the “lower heat sink” releasing heat to environment and the working fluid can reach again the “upper heat source” and restart the cycle.

The Efficiency of the Stirling Cycle is bound to Carnot Cycle that depends strictly on the difference of temperature between the hot and cold source.
Thermal heat is transmitted to the working fluid through the walls on the heat exchangers for the upper heat source and the cold one.

The upper heat source need a burner that produce a flue gas with at temperature level in the range 500℃-750℃. The flue gas release heat to the heat exchanger of the “upper heat source”. The flue gas can be further cooled to heat hot water for the CHP system and then cold flue gas is released to environment.
Also the “lower heat sink” can release heat useful to produce hot water for the CHP system.

Different type of working fluid can be utilised:

- Hydrogen (high viscosity, then lower friction losses, but flammable, corrosive and leakage from system, increasing the number of refill operation during life cycle)
- Helium (inert, with higher friction losses than hydrogen and safer, but expensive)
- Compressed air or nitrogen (compressed air contains oxygen that with its increased partial pressure may be risky due to presence of flammable lubricant. Nitrogen could be preferable, since it is inert and safe, although its energy density is lower than hydrogen, then size of engine should be increased)

Stirling engine exist in three main configuration:

Alpha: two separate pistons, always in contact with upper heat source and lower heat sink respectively. Working fluid moves in between, expanding and cooling. Pistons move and generate mechanical energy.

Beta: One cylinder, one piston and one displacer (piston). The cylinder in the lower part is in contact with the upper heat source, while the upper part is in contact with the lower heat sink. The displacer is utilised to allow the working fluid to move from the upper part to the lower part of the cylinder, thus allowing the heating or the cooling of the working fluid. The piston is pushed by the expanding working fluid and transmit the mechanical energy to a flywheel. Working fluid , when cooled, collapses and allows the piston to enter in the cylinder without consuming inertial energy of the flywheel. In the beta engine there are no friction part (sealing) in contact with the hot exchanger like the alpha engine (one of the two piston is always in contact with hot heat exchanger) and this is a technical advantage.

Gamma: a big cylinder with the displacement piston and a working piston in another smaller cylinder. The displacement piston allows the working fluid to be heated in contact to upper heat source and move to working piston releasing mechanical energy. Working piston is in contact with lower heat sink, then working fluid is cooled, collapsed and piston is pushed back to restart the cycle. This configuration is simpler and is often used in multiple cylinder engines.

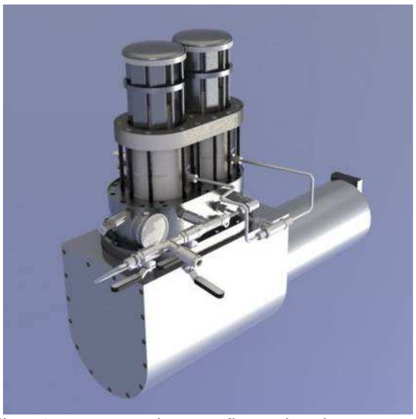


Figure 47. Stirling Gamma Engine configuration (www.genoastirling.com)

Uses of CHP based on ECE (Stirling) are mainly for small dedicated application. Up to now the cost per kWe produced is high and there are not large scale application.

This is a limit, if compared with "traditional" steam powered systems. But Stirling engine has some advantages, as

- Low noise
- Low rpm of cylinders
- Low maintenance
- Any kind of heat source to feed the upper heat source, better renewable biomass boiler.
- Seals are in the cold part of the engine for configuration beta and gamma, in this way it is possible to increase the life time of the engine and maintenance periods.

Stirling engine has also drawbacks, such as:

- Cost of the hot side heat exchanger, due to high temperature and corrosion issues.
- Constant working load: Stirling needs warm-up period and has not a wide range to modulate the power generated.

Constant working load is not a drawback if the requirement of the user is to have a low maintenance engine with constant speed engine.

The cost of a Stirling Engine per kWe installed is about 7000 €/kW.

Heat exchanger surface (and cost):
S HEX = (1/DT)^2
If we increase the ΔT of the two heat sources (upper and lower), then the cost of the heat exchanger decrease dramatically due to surface reduction to obtain same energy

ΔT C°	Cost [%]
10	100,00%
20	25,00%
30	11,11%
40	6,25%

output.

	50	4,00%

The System:

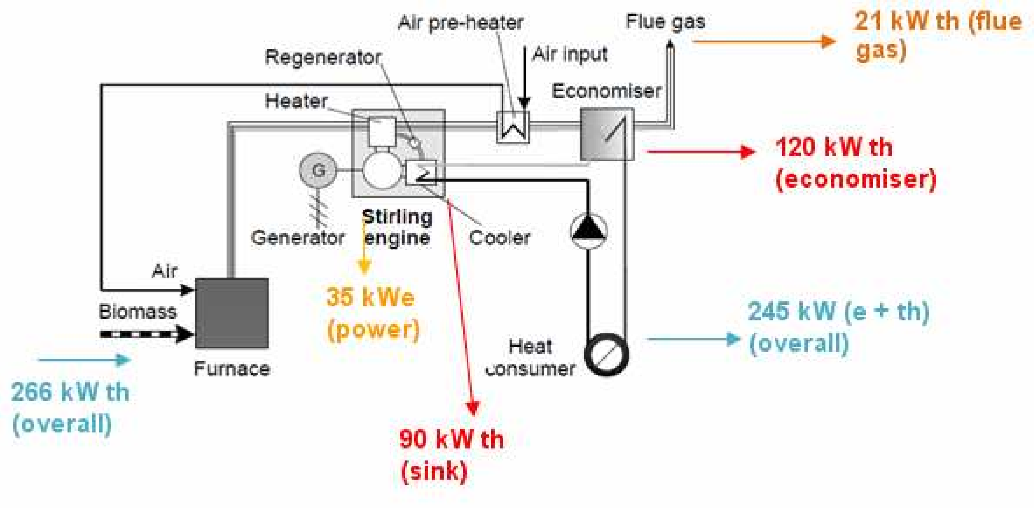


Figure 48. CHP with External Combustion Engine based on Stirling

The modelling of CHP with External Combustion Engine based on Stirling is defined by the following equations:

Some figures can explain quantities of electric power and thermal heat and relevant ratio:

Table 5. Explanation of electric power and thermal heat quantities and relevant ratio

			Overall ratio	Engine ratio
Total fuel energy	266	kW	100%	N.A.
Total heat for CHP	210	kW th	78,9%	N.A.
Total (heat and power)	245	kW	92,1%	N.A.
Power	35	kW e	13,2%	28,0%
Thermal power (engine out)	90	kW th	33,8%	72,0%
Engine (total inlet)	125	kW th	47,0%	100,0%

In general:

$$H_{fuel} = H_{requested} + P_{e} - H_{flue\ gas\ out} \quad (4.4.1)$$

where:

$$H_{fuel} = Q_f * \Delta H_f \quad (4.4.2)$$

where:
Q_f = fuel flow rate [kg/h];
ΔH_f = fuel enthalpy [kJ/kg]

$H_{requested}$ (heat delivered to heating system):

$$H_{requested} = Q_w * cp * (T_{supply} - T_{return}) \quad (4.4.3)$$

where:
P_e = fuel flow rate [kg/h];
$(T_{supply} - T_{return})$ = Water temperature for supply/return (℃)

4.5. CHP with Steam Injection Gas Turbine (STIG) and Heat Recovery Steam Generation (HRSG)

Steam-injected gas turbines are mostly used for small-to-medium-size cogeneration of power and steam in industry (e.g. food industries, breweries, chemical and paper industries) and community facilities (e.g. hospitals, universities, district heating), especially in applications where the steam load or the electricity price varies. In a cogeneration system, the steam demand often determines the operation. A system consisting of a simple cycle gas turbine and an HRSG (heat recovery steam generator) is efficient for constant heat demand, whereas the system is inefficient at reduced heat demands, since the steam production or the gas turbine power output must be reduced; however, in a steam-injected cycle, the steam not needed for other purposes can be injected in the gas turbine for increased power generation. A duct burner can be installed before the HRSG to increase the steam production.

A schematic of a generic steam-injected gas turbine cycle is shown in Figure 49.

The steam-injected gas turbines available in the Gas Turbine World Handbook have been summarized in Tab. 6.

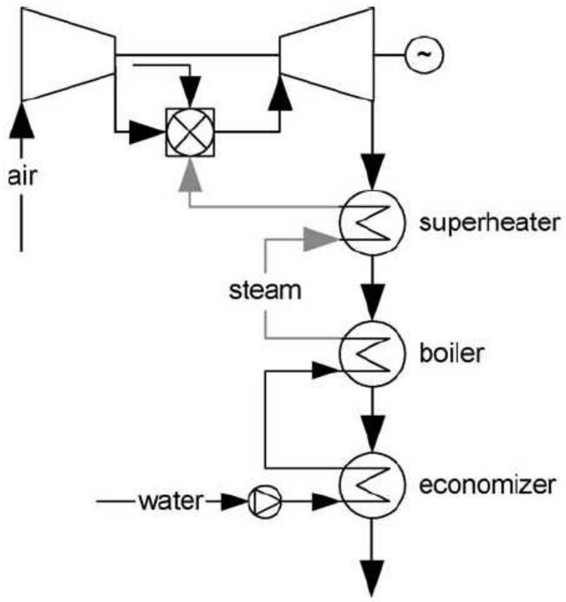


Figure 49. Schematic steam-injected gas turbine cycle with tail Heat Recovery Steam Generator (HRSG)

The first commercial steam-injected cycle was the 501-KH5, also called “Cheng cycle” after his inventor, started operation in 1985 at a university in California and generated power and steam for space heating and cooling; surplus power could be exported to the grid. The 501-KH5 was based on the single-shaft aeroderivative Rolls-Royce Allison 501-KB gas turbine. This gas turbine has a large compressor surge margin, which enables injection of all the steam generated from the exhaust gas without compressor stalling. The Kawasaki M1A-13 gas turbine has also been converted to a Cheng version, the M1A-13CC, and the first plant started operation in Japan in 1988. Since then, over a hundred Cheng cycles have been installed. In addition, there are retrofit Cheng steam injection systems for GE (General Electric) industrial gas turbines, suitable for gas turbines used for peaking power generation or cogeneration.

A Cheng version of the steam-cooled GE 7H gas turbine was calculated to have an efficiency of 60.5% and a power output of 600 MWe. A Cheng version of the GE LM2500 gas turbine with an efficiency of 44.5% has been designed. The simulated power output and efficiency of the Cheng cycle were relatively unaffected by high ambient temperatures.

Table 6 - Available steam-injected gas turbines (Gas turbine world Handbook; 2005)

Manufacturer	Model	P (MW_e)	η_{el} (%)	PR	TIT (°C)	m_{steam} (kg/s)	m_{air} (kg/s)
Cheng cycles							
Rolls-Royce	501-KH5	6.4	39.9	10.2	N/A	2.7	18.4
Kawasaki heavy industries	M1A-13CC	2.3	31.9	8.9	N/A	1.4	8.5
STIG cycles							
Ishikawajima-harima heavy Industries	STIG-LM1600	16.9	39.7	25.1	735	2.5 (1.5 + 1.2)	52.6
GE aero energy products	LM2500 STIG (50 Hz/ 60 Hz)	26.5/27.8	39.4/40.6	20.0	N/A	2.3 +4.0	75.8
Ishikawajima-harima heavy Industries	STIG-IM5000 (50 Hz/ 60 Hz)	50.1/51.2	42.9/43.9	30.6	788	10.4+9.1	156.0
Aquarius							
Mashproekt	Aquarius-16	15.5	41.7	20.0	N/A	5.6	44.8
Mashproekt	Aquarius-25	25.0	42.0	17.9	N/A	8.1	72.7
Mashproekt	Aquarius-40	40.7	42.8	19.8	N/A	12.9	93.5
Miscellaneous							
Ishikawajima-harima heavy industries	IM400 IHI-FLECS	6.2	35.7	12.4	1010	N/A	18.2
Kawasaki heavy industries	M7A-01ST	6.6	32.9	12.7	N/A	1.7	22.2

GE offers steam injection systems (STIG) for power augmentation of their aeroderivative gas turbines. The first STIG system started operation in 1985 at a paper mill in California, where a LM5000 gas turbine was retrofitted with partial steam injection of high-pressure steam in the combustor and the high-pressure compressor discharge. Steam injection increased the power output from 29.9 MWe to 41.9 MWe and the efficiency increased from 36.0 to 41.8% and the NOx levels were below 25 ppmvd (parts per million by volume, dry, 15% oxygen). The LM1600, LM2500 and LM5000 gas turbines have been converted to STIG versions.

The performance of a steam-injected cycle can be summaried by the overall heat balance reported in Eq.(4.5.1),

$$m_{fuel} \cdot LHV = P_{el} + m_{steam} \cdot (h_{steam} - h_{water}) + Losses \qquad (4.5.1)$$

where

m_{fuel}	fuel flow [kg/s]
LHV	Lower Heating Value [kJ/kg]
P_{el}	electrical power [kW]
m_{steam}	steam flow directed to heat cogeneration [kg/s]
h_{steam}	steam enthalpy [kJ/kg]
h_{water}	return water enthalpy [kJ/kg]
Losses	mechanical and electrical losses (~2% of the fuel input), stack losses (~30-60% of fuel input, depending on the quantity of steam directed to heat cogeneration or turbine injection) [kW]

4.6. CHP based on fuel cells and gas reformer

CHP based on Fuel cell and gas reformer is able to produce both power and thermal energy, at a temperature level that can be utilised for heating purposes.

The system combines the gas processor unit (to convert a liquid or gaseous fuel into gaseous hydrogen) and a FC, usually a PEM, that produces power and thermal energy.

Also the gas processor produces a certain amount of heat that is recover and made available for heating purposes.

Control system is part of the CHP, in order to monitor and control all the process parameters.

The inverter is able to convert DC to AC, asking power to the Fuel Cell module. The inverter discharges power to the EMCS that delivers the power to the points of use or to the grid.

The inverter shall be synchronised with the frequency of the grid prior to extract power from the Fuel Cell and deliver it to EMCS/grid.

The air blower is another crucial component of the CHP and for stationary application it is a source of "power disruption" that decrease the overall efficiency of the system, since consumes electric power to blow the air into the cathodes. The blower consumes less energy if the membrane stacks are suitable build, i.e. with low pressure drops. In fact, more bigger the space in the reaction chamber, the less the pressure drop and the energy consumed by the blower.

Water is produced by the Fuel Cell and the flue gas exiting the cathode is rich of humidity. This humidity is collected in a membrane device, that let the water humidity pass from the flue exhaust gas to the inlet air. Sometimes this humidification is not sufficient, then an additional demineralised water spraying system is installed in the inlet air.

Demineralised water (about 0.5 microS/ cm) can be produced with ultra-filtration cartridge or with cartridges filled with cation/anion exchange resin. Demi water is also produced for the Water Gas Shift Reaction in the gas reformer.

PEM FC to reach very fast 100% of nominal production needs to be already "warm" (i.e. close to optimal working temperature 55℃-65℃). This can be reached keeping the cooling water at suitable temperature. Otherwise you should consider a warm-up period, where the FC is run at 50-60% of nominal production. This period can last several minutes, depending on the starting temperature of the cooling water and how big is the FC stack (thermal inertia).

The CHP based on FC and gas reformer is not a flexible system, since there are internal recirculation of gas and water, to optimise the gas reforming and the Fuel Cell running.

Usually these kind of CHP are run at fixed point, asking the system to deliver thermal energy for heating purposes, in a manner called "thermally driven CHP". Electrical energy is produced, but can be considered as a by-product, since it is produced not in accordance to the user request profile.

Different resolutions for the CHP, other than heating could be the utilisation to provide extended run backup power to mobile network sites when there is loss of electrical power due to severe weather conditions or limited grid capacity.

In this case, the power needs are predominant and the heat is not necessary.

These small FC systems can be preferred because it can lower the greenhouse emissions and the carbon footprint, with a system that is able to fulfil critical backup power applications without limiting the performances, reliability and long autonomy and minimising the maintenance.

IdaTech's ElectraGen, for instance, "burns" (in the gas processor) methanol and water to produce hydrogen and carbon dioxide. Temperature is lower than conventional combustion, thus lowering the production of NOx.

The reaction is: $CH_3OH + H_2O = 3H_2 + CO_2 + heat$ (in the gas processor)
$3H_2 + 1.5\ O_2 = 3\ H_2O$ + electric power and heat (in the Fuel Cell)

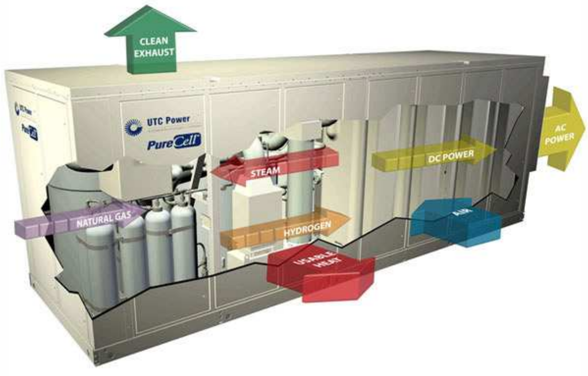


Figure 50. Internal view of a package, including reformer, FC stack 50 kWe, demi water production (from UTC power website)

The modelling of CHP based on Fuel cell and gas reformer is defined by the following equations:

In general:

$$H_{fuel} = H_{requested} + P_e - H_{flue\ gas\ out} \qquad (4.6.1)$$

where:

$$H_{fuel} = Q_f * H_f \qquad (4.6.2)$$

Q_f = fuel flow rate [kg/h];
H_f = fuel enthalpy [kJ/kg]

H requested:

$$H_{requested} = Q_w * c_p * (T_{supply} - T_{return}) \qquad (4.6.3)$$

Q_w = water flow rate [kg / h]
c_p = specific heat of water [kJ / kg K]

And P_e is the electric power made available at the inverter (AC power) in kW_e (taking into account the losses of energy due to instrumentation, air blower, water pumps):

$$P_e = P_{stack} - P_{pump} - P_{blower} - P_{instr} \qquad (4.6.4)$$

PER is the result of:

$$PER = \frac{P_e + H_{requested}}{H_{fuel}} \qquad (4.6.5)$$

4.7. CHP based on hybrid PV/Thermal

A PV-Thermal module is a thermal collector into which a PV module is integrated, in such a way that the PV module not only generates electricity, but simultaneously functions as the thermal absorber of the thermal collector. The idea behind this combination of technologies, is given by the fact that a PV module converts only a small part of the absorbed irradiance to electricity, while the largest part of the absorbed irradiance is converted to heat, leading to significant heating up of PV modules in full sun. In a PV-Thermal module, this heat is extracted and used for e.g. tap water heating or space heating, increasing the total energy output of the module.

Different types of PV-Thermal collectors exist. The most important distinctions are

- air-collector or liquid-collector PVT: the number of air-collectors is small relative to liquid-collectors, but since PV is more easily integrated in an air-carrying system, relatively many PVT modules are air collectors. Air has a low density and low thermal capacity, so air collectors have very large volume flows compared to liquid collectors, leading to large channels. Also, air has a low thermal conductivity, leading to lower heat transfer.
- glazed or unglazed PVT: this mainly affects the insulation level of the collector. Therefore, glazed collectors can produce higher temperature heat, but also the stagnation temperatures are much higher, which is often a problem for PVT applications.
- concentrating or flat-plate PVT: in concentrating PV systems, active cooling of the PV may be desirable to prevent too high PV temperatures that lead to reduced PV performance or even damage. If an application is at hand for this heat, it is convenient to use this system as a PVT system. A problem in concentrating systems is always the potential risk of stagnation. Because stagnation temperatures in concentrating systems tend to be very high, a control system has to move the PV out of focus as soon as the heat extraction stops.

Figure 51. PVT collectors (a) Concentrating collector, (b) Unglazed PVT air collector, (c) glazed PVT liquid collector.

The thermal efficiency of a PVT collector is lower than that of a conventional solar collector of the same size. Depending on the type of PVT (glazed or unglazed), the PV efficiency is lower than or similar to a conventional PV module.

- The electrical efficiency of a PVT collector depends on the type of PV used in the PVT (see the section on PV), the reflection losses occurring at the top glass (for glazed PVT), and the temperature of the collector medium flowing through the collector, which is a result of the dimensioning of the PVT system relative to the heat demand.
- The thermal efficiency of a PVT collector is somewhat lower than the thermal efficiency of a thermal collector, due to the reflection losses at the PV absorber, the fact that the PV is not spectrally selective (leading to large radiative heat transfer between the PV and the top glazing), and the fact that part of the incoming radiation is converted to electrical energy, and therefore, cannot contribute to the thermal output anymore. Note that if a PVT collector is not producing electricity, its thermal efficiency is increased. The effect of these issues on the thermal efficiency curve is indicated in the figure below.

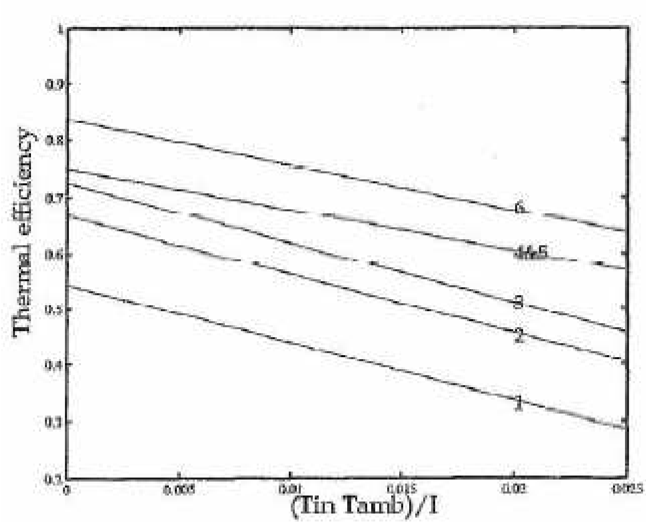


Figure 52: The efficiency curves vs. reduced temperature, successfully removing the special temperatures of the combi-panel. From low to high: (1) combi-panel, (2) optical efficiency enhanced, (3) heat transfer enhanced, (4) spectral selectivity enhanced, (5) heat conduction sideways through silicon removed, (6) no electricity produced.

It is recommended to calculate the thermal and electrical yield of a PVT module according to the following equations:

$$\frac{P_{el}}{A_{PVT}} = \tau\eta_{0,electrical}\left(1-\beta\left(T_{PV} - 25^{o}C\right)\right) \qquad (4.7.1)$$

$$\begin{aligned}\frac{P_{therm}}{A_{PVT}} &= F_R\left(\tau_\alpha - \tau\eta_{el}\right)I_{solar} - k_1\left(T_f - T_a\right) - k_2\left(T_f - T_a\right)^2 \\ &= F_R\tau_\alpha I_{solar} - F_R\frac{P_{el}}{A_{PVT}} - k_1\left(T_f - T_a\right) - k_2\left(T_f - T_a\right)^2\end{aligned} \qquad (4.7.2)$$

Here, τ is the transmission of the upper glass plate (for a glazed PVT about 0.92, for an unglazed PVT τ =1), β is the temperature coefficient (depends on PV material, see section on PV), $\eta_{0,electrical}$ is the electrical efficiency of the PV under standard test conditions (see section on PV), F_R is the heat removal factor, which is a measure for the efficiency of the absorber for transferring heat to the collector medium, which is typically in the order of 94-96% for a glazed PVT and 85-90% for an unglazed PVT, τ_α is the effective light absorption in the PVT, and can be approximated by $\tau x \alpha$, in which α depends strongly on the type of PV. A range of absorption factors for typical PV types is shown below. Note the large range for a-Si modules. For PVT modules, k_1 is typically of the order of 5-6 W/m^2K, while k_2 can be ignored.

Table 7: Typical module absorption factors for different PV types (data from Santbergen, 2008).

	Module absorption factor	
	Min	Max
c-Si	80%	94%
a-Si	68%	89%
CIGS	92%	94%

Key performance indicators

- Power range (W): Electrical power: 160-0 W/m2, Thermal: 700-0 W/m2.
- Cost of the equipment (€/kW): about 500-1000 euro/kW combined electrical and thermal, being the sum of solar thermal and PV.

5. Cooling Generation

5.1. Compression Chiller

A compression chiller is a device able to deliver "cooling" to buildings (utilising cold air) or cooling water for process or conditioning purposes.

A compression chiller works like an "inverted" heat pump, because the compression chiller cools the internal part of the building and delivers the heat outside in the environment.

A compressor chiller utilised electrical energy to perform the compression work.

The compressor chiller cools the internal part of building with a cold indoor coil called "evaporator". The condenser, a hot outdoor coil, releases the collected heat outside. The evaporator and condenser coils could be serpentine tubing surrounded by aluminium fins. This tubing is usually made of copper or could be a serpentine submerged by water or a cooling fluid like a mixture water/glycol.

The compressor (a pump) circulates a heat transfer fluid (or refrigerant) between the evaporator and the condenser. The compressor forces the fluid through the circuit of tubing and fins in the coils.

The refrigerant fluid evaporates in the evaporator coil, pulling heat out from the internal building lowering the temperature. The hot refrigerant gas is pumped outdoors into the condenser where it is condensed back to liquid, releasing the heat to the outside environment through the metal tubing and fins or to cooling water circuit (at 30°-35℃) that release the heat in a co oling tower.

The refrigerant fluid in the compressor chiller shall be classified as CFC-free.

The refrigerants used in the chillers sold in Europe are mainly R410a (70%), R407c (20%) and R134a (10%). Mainly compression chillers are utilised for:

– Process and HVAC duty:

These equipments are utilised for the production of "chilled water" that is utilised in the industry for all the services that need "cooling water". The compression chiller produce cooling water at different temperature levels, but decreasing the performances if we move from the optimal +7° / +12℃. These compressor have an evaporator that cools down water and release the heat outside in a forced air battery (with a fan) or a cooling tower.
This kind of chiller is utilised to produce cold water for the HVAC batteries (typical temperature level for air conditioning is +7° / +12℃).

According to size of compression chiller and environmental conditions it could be possible to utilise a forced air battery (with a fan) or a cooling tower.

In the evaporator the hot water shall not exceed 45℃, otherwise the compression chiller cannot work properly. Usually there is an alarm that stops the chiller. To avoid this problem a chiller water tank is installed in order to shave the peaks of temperature and it is possible to divert the produced chilled water to cool down the water in the tank, prior to enter the compression chiller.

– Home duty:

These chillers are utilised for domestic air cooling and conditioning. The evaporator and the condenser exchange heat through air heat exchangers.

There are two main group of compression chillers: single unit and split units.

Single unit compressor chiller is a compact unit with an air duct that release hot air through an opening in a side wall, while split unit may have one or more evaporators in the rooms, insulated piping for the refrigerant and a condensation unit outside the building.

The home compressor chillers are able to manage different level of internal and external temperature. The evaporator needs a water drain to remove the condensed humidity of the indoor air.

Figure 32. Compressor chiller (http://www.liquidchillers.org)

The cold delivered by the compression chiller is the heat extracted from the evaporator. The heat released in the condenser is the heat from the evaporator plus the compressor work of the pump.

The steady-state performance of a compression chiller at a given set of temperature conditions is referred to Energy Efficiency Ratio (EER).

The EER is between 2.2 to 3.2 according to the efficiency of the system. Higher EER means higher efficiency.

As an overall Key Performance Indicator we introduce the PER (primary energy ratio), which is simply the ratio between useful energy output divided by the necessary energy input. This ratio is a measure of the overall efficiency of a heating/cooling system, taking into account the energy losses related to the generation of electricity. A higher PER corresponds to a more energy-efficient system.

Since the compressor chiller utilises electric energy and the generation and distribution rate for electrical energy in Europe is about 40%, PER of this system is

$$PER = EER * 0.40 \qquad (3.6.1)$$

if EER is 3.2, then PER is 1.28.

Compressor chillers can range from one single dwelling unit (about 1000 W) up to large industrial compression chillers (1000 kW thermal capacity).

Compressor chillers have an average price of around 370 €/kW (th) installed.

The modelling of compressor chiller is defined by the following equations:

- Requested Cooling [W]: the heat flow requested to be removed from the evaporator:

$$H_{requested} = H_{supply} – H_{return} = Q * cp * T_{supply} – Q * cp * T_{return} \qquad (3.6.2)$$

- Supply temperature [^{o}C]. Defined according to the needs of the user:

$$T_{supply} = H_{supply} / Q * c_p \qquad (3.6.3)$$

where:
Q = water flow rate [kg / h]
c_p = specific heat of water [kJ / kg K]

- Return temperature[ºC]. Defined by the heating delivered through the cooling circuit:

$$T_{return} = T_{supply} – H_{requested} / Q * c_p \qquad (3.6.4)$$

- EER (Energy Efficiency Rate) [-]:Ratio between the output heat and the electricity consumption of the system:

$$EER = H_{requested} / P \qquad (3.6.5)$$

where:
EER = energy efficient ratio (-)
$H_{requested}$ = net cooling capacity (W th)
P = electrical power (W e)

- Buffer capacity [J]. Calculated from difference between supply and return temperatures, heat capacity of the used storage material, density and buffer size (volume):

$$BC_{max} = cp_{water} * \rho_{water} * V * \delta T \qquad (3.6.6)$$

- SoC (state of Charge) [-] of the buffer. Calculated from the actual buffer temperature, supply- and return temperatures, being constant the T supply and T return Let "BC" be the actual Buffer Charge (i.e. SoC of the buffer):

$$SoC = BC_{max} - (Q*cp*T_{supply} *time) \qquad (3.6.7)$$

where:
time = timeframe within water is supplied at T supply

- Electrical power [W]. Electric energy consumed by the compressor chiller pump:

$$P = H_{requested} / EER \qquad (3.6.8)$$

- Heat discharged to condenser [W] (air cooling or water cooling tower):

$$H_{condenser} = H_{requested} + P \qquad (3.6.9)$$

$$H_{condenser} = H_{requested} * (1+EER)/EER \qquad (3.6.10)$$

where:
$H_{requested}$ = net cooling capacity (W th)
P = electrical power (W e)

5.2. Absorption Chillers

Absorption chillers (Figure 30) are driven by hot water instead of electricity: a relatively small amount of power is only used for auxiliaries. Hot water may come from any number of industrial sources including waste heat from industrial processes, prime heat from solar thermal installations or from the exhaust or water jacket heat of a piston engine or turbine.

Figure 30. A commercial absorption chiller

With reference to Figure 31, as water evaporates in the evaporator, it cools the chilled water. After a functioning point, though, the adsorber is saturated - cannot adsorb any more water- and needs regeneration. This regeneration needs high temperature, which comes from hot water
Absorber cooler units use thermal energy to cool a solution of H_2O and NH_3 (or H_2O and $LiBrO_2$). Absorption machines have a wide range of applications: their advantage is the possibility, in summer period, of employing thermal energy, not required by users, to generate cold energy, whose load profile gets higher in summer months.

The thermodynamic cycle of an absorption chiller is driven by a heat source, delivered to the chiller via steam, hot water, or combustion. Compared to electrically powered chillers, absorption chillers have very low electrical power requirements for both the solution pump and the refrigerant pump. The Coefficient Of Performance, COP, varies from 0.5 (single effect) to 1.0 (double effect). From an energy-efficiency point of view, they represent a good solution where waste heat is readily available. In extremely sunny climates, thermal solar energy can be used to feed absorption chillers. Single effect absorption cycles often use H_2O (refrigerant) and LiBr (absorbent) solutions.

Figure 31 shows a general single-effect absorption chiller plant lay out: industrial chillers typically come as complete, packaged, closed-loop systems, including the chiller unit, condenser and pump station with recirculating pump, expansion valve, no-flow shutdown, internal cold water tank, and temperature control. The internal tank helps maintain cold water temperature and prevents temperature spikes from occurring. Closed-loop industrial chillers recirculate a clean coolant or clean water with condition addititives at a constant temperature and pressure to increase the stability and reproducibility of water-cooled machines and instruments. The water flows from the chiller to the application's point of use and back.

If the water temperature differentials between inlet and outlet are high, then a large external water tank would be used to store the cold water. In this case the chilled water is not going directly from the chiller to the application, but goes to the external water tank which acts as a sort of "temperature buffer." The cold water tank is much larger than the internal water tank. The cold water goes from the external tank to the application and the return hot water from the application goes back to the external tank, not to the chiller.

The less common open loop industrial chillers control the temperature of a liquid in an open tank or sump by constantly recirculating it. The liquid is drawn from the tank, pumped through the chiller and back to the tank. An adjustable thermostat senses the makeup liquid temperature, cycling the chiller to maintain a constant temperature in the tank.

One of the newer developments in industrial water chillers is the use of water cooling instead of air cooling. In this case the condenser does not cool the hot refrigerant with ambient air, but uses water cooled by a cooling tower. This development allows a reduction in energy requirements by more than 15% and also allows a significant reduction in the size of the chiller due to the small surface area of the water based condenser and the absence of fans. Additionally, the absence of fans allows for significantly reduced noise levels.

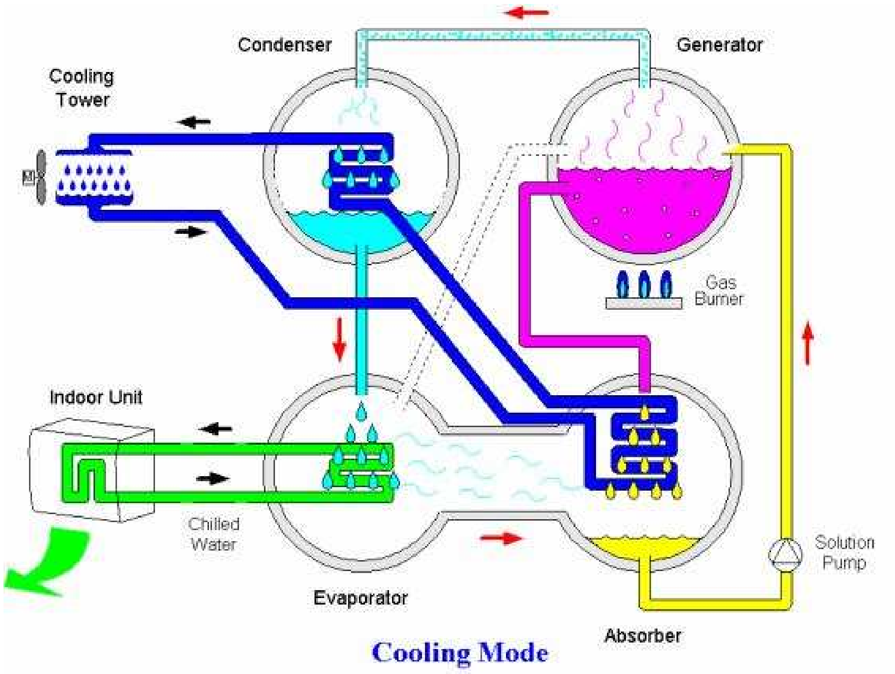


Figure 31. Scheme of an absorption chiller

Technical features of a typical commercial absorber (LS LWM-W003) have been summarized in Tab. 1: the absorber considered here presents a nominal cooling power equal to 102 kW, with 140 kW thermal inlet power and a consequent nominal COP value of 0,7.

COP is defined as cooling power and thermal power ratio, as indicated in Eq. (3.5.1).

$$COP = Pc/Pt = Mc * (TWCC2-TWCC1) / [Mh * (TWCH1-TWCH2)] \quad (3.5.1)$$

Table 3. Absorber LS LWM-W003 technical features

Cooling power	**kW**	**50**	**80**	**96**	**102**
Hot water side					
Mass flow M_h	m^3/h			9	9.2
Hot water inlet temperature TWCH1	℃	85.0	85.0	90	95
Hot water outlet temperature TWCH2	℃	73.5	74.0	77	82
Pressure losses	mH2O	0.70	2	1.8	2.1
Cooled water side					
Mass flow M_c	m^3/h	8.72	13.9	16.7	17.7
Cold water inlet temperature TWCC1	℃	12.0			
Cold water outlet temperature TWCC2	℃	7.0			
Pressure losses	mH2O	0.70	1.6	2.3	2.4
Cooling tower circuit					
Mass flow	m^3/h	20.70	33	39.2	41.7
Water inlet temperature	℃	28.0			
Water outlet temperature	℃	33.0			
Pressure losses	mH2O	0.80	2	2.8	3.4

6. Thermal Energy Storage

6.1. Sensible heat

6.1.1. Tank storage

A typical device for thermal storage (sensible heat storage) is a tank filled by a liquid (usually water) which changes temperature but not phase during operations. It can be connected directly, or through a heat exchanger, to the main thermal distribution circuit. Sensible heat storage systems are simpler in design (Fig.1) than latent heat or bond storage systems. However, they suffer from the disadvantage of being bigger in size. This vessel is able to store heat through the liquid and the insulation thermal capacitance.
The storage capacity of a sensible heat storage with a liquid medium is given by

$$Q_s = mc\Delta T = V\rho c\Delta T \qquad (5.1.1.1)$$

where *m* is mass, *V* is volume, *c* is specific heat, ρ is density and $\Delta T = T_{max} - T_{min}$ is maximum temperature difference between maximum and minimum temperatures of the medium. This expression can be used to calculate the mass and volume of storage material required to store a given quantity of energy.

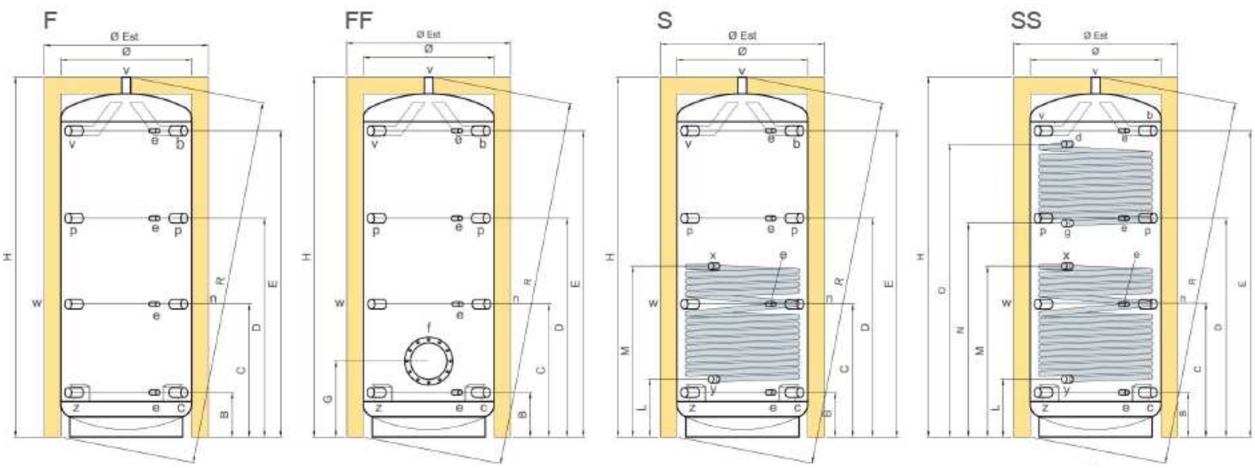


Figure 53. Examples of storage tanks (S and SS configurations include coils for solar panel connections).

With its high specific heat water is the most commonly used medium in a storage tank. For instance, most solar heating systems use hot water storage tank located either inside or outside of the buildings (or underground). As shown in Figure 53 (see S and SS cases) some manufacturers build water tanks equipped with coils for solar panel connections. The sizes of the tanks used vary from few hundred litres to few thousand cubic meters. An approximate thumb followed for fixing the size is to use about 75-100 litres of storage per square meter of collector area. In general, since its volume is related to thermal endurance (to satisfy thermal loads without generating), for tank size it is also necessary to take into account cost and space reservation aspects. If the problem is well optimized it is possible to reduce fuel consumption operating the generators at full load condition (during charging phase) and switch off the machines for significant operative periods. The additional cost related to the tank (and valves) is well absorbed by fuel consumption decrease if vessel size is well designed in agreement with thermal loads requested by users.

Figure 54. Example of a thermal insulated storage tank for water.

Water storage tanks (see Fig.2 for an example) are made from a variety of materials like steel, concrete and fibreglass. They are usually insulated with glass wool, mineral wool or polyurethane. The thickness of insulation is large, ranging from 10 to 20 cm. For this reason, insulation cost represents a significant part of the total cost and it is necessary to analyse any mean to reduce this cost. Moreover, in an underground tank, the insulating value of the earth surrounding the tank may be adequate and this could provide the bulk of the insulation thickness required. However, it may take as much as one year for the earth around a large storage tank to reach a steady-state condition by heating and drying, and a considerable amount of energy may be required for this purpose. If water is at atmospheric pressure, the temperature is limited to 100℃. It is possible to store water at temperature a little above 100℃ by using pressurized tanks.

The thermal storage approach is based on charging and discharging procedures. The tank is charged when heat demand is lower than thermal generation: in this case the tank is fed by high temperature water (from generators) to have an increase in its average temperature. Moreover, the discharging procedure starts when it is necessary to satisfy a heat demand higher than thermal production: in this second case the high temperature water stored inside the tank is used to supply a part of (or the whole) requested thermal load. Since all tank storages have a stratified configuration in terms of temperatures, it is necessary to carefully manage both charging and discharging procedures with apt valves. For instance, during a discharging phase it is useful to take water from the top of the tank because it is at the highest temperature. So, in comparison with phase changing devices, sensible heat storage cannot store or deliver energy at a constant temperature.

6.1.2. Aquifer Thermal Energy Storage (ATES)

An aquifer thermal energy storage system (ATES) is a storage system for low enthalpy thermal energy in natural water-bearing underground layers (the aquifer). The transfer of thermal energy from and to the aquifer is realized by extracting and re-injecting ground water from one or more wells and as such, this system is considered an “open” system. In summer, the relatively cold groundwater (8-12℃) is extracted for the cooling of buildings. This involves heating the groundwater, typically to values between 15 and 20℃ and subsequently re-injecting it into the aquifer. During the heating season, the warm groundwater is either used in combination with a heat pump to provide heating for buildings or a cooler is used to cool the groundwater again (See more detailed information in Annex C).

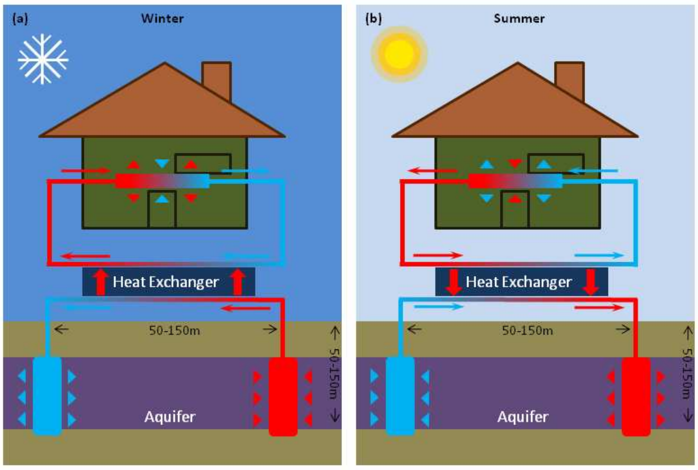


Figure 55. Operation principle of a doublet ATES system during (a) winter and (b) summer.

There are three main ATES types:

– Doublet configuration:

The most common ATES configuration consists of a pair of wells: a cold and a warm well (Fig. 55). The distance between each injection and extraction well is usually between 50 and 250 m to prevent a thermal breakthrough between the wells (mixing of cold and warm water)[5,6]. In summer, when cooling is desired, cold groundwater from the cold well is used to dissipate heat from the building circuit. The heated water is subsequently injected into the second well (warm well). In winter, this process is reversed (cyclic/bidirectional system). Consequently, in summer heat is stored for use during the winter, while in winter cold is stored for use during the summer and hence, one also refers to ATES as a seasonal storage system, having a storage time of roughly 6 months.

– Mono source configuration:

In this configuration, only one source is drilled for the extraction and injection. The required physical separation between the warm and cold well is realized by a vertical separation rather than lateral. Evidently, this design requires an aquifer with a sufficient thickness. Ideally, a less permeable layer is located in between the wells. Due to the lower investment cost as compared to the doublet set-up, this design is especially suited for smaller installations with limited power outputs.

– Recirculation configuration:

Recirculation is similar to the above mentioned ATES configurations except for the direction of the groundwater flow which is the same all year round (continuous/unidirectional system). There is only one extraction/injection well: In summer, the cold groundwater is extracted to provide natural cooling and the warm water is subsequently reinjected into the injection well. To prevent thermal pollution of the underground (and the concomitant decrease in system performance) the groundwater is cooled below the natural groundwater temperature during winter and injected into the well. This cooling can be achieved through the use of a cooling tower, heat pump, air handling unit, etc.. The system should be dimensioned in such a way that over time no net heating or cooling of the underground occurs. The advantage of this system is that cooling can be provided all year round and that the implementation is simpler and cheaper as compared to a cyclic system. This configuration is commonly used in industry since cooling is required all year long.

In an ATES system, the aquifer serves as the storage medium and as far as the hydrogeological characteristics of the underground allow, these systems are most suited to high capacity systems. The existing powers range in size from less than 50 to over 10000 kW [7], and capacities of 15 kWh_{th}/m^3 have been achieved [8]. An important parameter for the feasibility of an ATES system is the aquifer storativity (S), defined as the amount of water (dV_w) that can be stored or released by an aquifer per unit decline in hydraulic head (dz) and per unit area of the aquifer (A) [9]:

$$S = \frac{dV_w}{A \cdot dz} \qquad (5.1.2.1)$$

Apart from the underground characteristics, the storage capacity of an ATES system depends largely on the installed HVAC equipment, the balance between heat and cold extraction, and climate conditions.

When modelling an ATES system, the storage efficiency can be expressed in terms of the Heat Recovery Factor (HRF) as follows [10]:

$$HRF = \frac{Q_{out}}{Q_{in}} = \frac{\int_{t,out} \left[V_{out}(t) \cdot \rho \cdot c_p \cdot \left(T_{out,w}(t) - T_{out,c}(t) \right) \right] dt}{\int_{t,in} \left[V_{in}(t) \cdot \rho \cdot c_p \cdot \left(T_{in,w}(t) - T_{in,c}(t) \right) \right] dt} \qquad (5.1.2.2)$$

Where ρ and c_p are the density and specific heat capacity of the groundwater, respectively, and the thermal energies, volumes and temperatures are defined in Fig. 56:

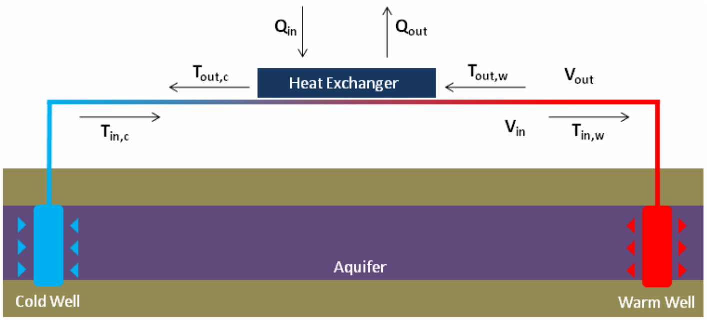


Figure 56. Notation of the parameters for modelling a doublet ATES system.

The coefficient of performance (COP) of an ATES system is defined as the delivered cooling/heating divided by the electricity consumption, and typically amounts to 20-40 for natural cooling, while a conventional chiller has a COP of 2.5-3.5 in the 6/12℃ regime. In combi nation with a heat pump, these installations reach a COP of 4-6 for heating. Overall, these systems are one of the most energy efficient systems for heating and cooling.

The investment cost strongly depends on the power of the system, *i.e.* the extracted ground water flow. An ATES system costs between 500 €/kW for larger systems and 800 €/kW for smaller systems. This amount covers the whole installation of the system including drillings, filters, heat exchanger, pipes, etc.. The heat pump (175-250€/kW_{th}), however, is not included. The ATES system has a life expectancy of about 20-30 years and maintenance cost are estimated to be 2% of the total investment [11]. An evaluation of tertiary buildings in The Netherlands revealed that the return of investment time is generally below 6 years [12,13]. Evidently, the economical feasibility of ATES systems largely depends on current energy prices and governmental subsidies. On average, an ATES system implementation realizes a reduction of 60% on the electricity and 50% on the natural gas consumption as compared to a conventional reference system. This corresponds to an average CO_2 emission reduction of 60% [12].

Potential risks of the installation of an ATES system include (all of which can be eliminated by proper dimensioning and installation):

- Mixing of groundwater with different qualities (salt – fresh water)
- Leaking of glycol or other cooling liquid
- Disturbance of the water level by extracting/injecting groundwater
- Thermal pollution of the underground.

Information of a real case study can be found in the document "Energy performance evaluation of aquifer thermal energy storage" (Authors: Koen Allaerts, Thomas Nuytten, Johan Van Bael) which is available in the webpage.

6.1.3. Borehole Thermal Energy Storage (BTES)

Borehole thermal energy storage (BTES) is a method for storing thermal energy in the underground. The thermal energy is supplied to and extracted from the underground by means of vertical heat exchangers mounted in boreholes. These heat exchangers are connected to a closed hydraulic circuit carrying the transfer fluid. By integrating multiple boreholes and heat exchangers a large storage capacity can be created for either low enthalpy thermal energy (heat and cold) or for high temperature heat (<100℃) (See more detailed information in Annex C).

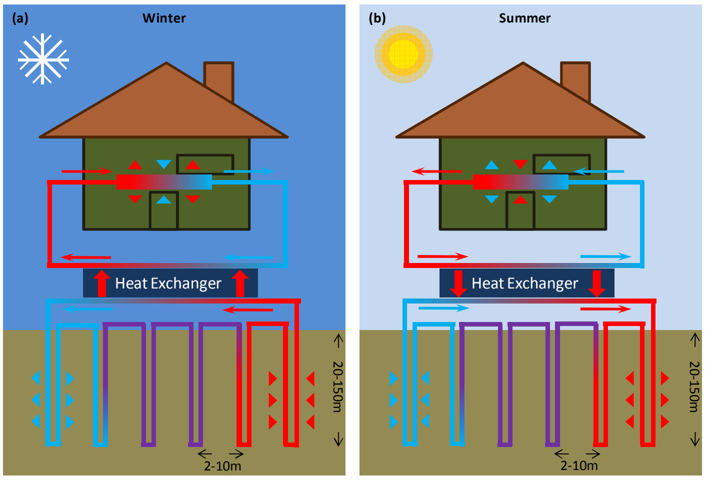


Figure 57. Low enthalpy BTES system operation principle during (a) winter and (b) summer.

- Low enthalpy BTES

A common BTES system consists of plastic loops serving as heat exchangers, inserted into a grid of boreholes, generally 20 to 150 m deep and 2 to 10 m apart. The number and depth of boreholes will determine the storage volume and thus the maximum power of the system. A schematic layout of a BTES system is shown in Fig. 57. The loops are connected to a closed hydraulic circuit carrying water to transfer the heat to the underground. Generally, glycol is added to the water as antifreeze.

In winter, the water/glycol mixture is presented to a water-air/water heat pump for the heating of the building. The transfer fluid which is cooled down by this process is subsequently pumped through the vertical ground heat exchangers to extract heat from the underground and to heat up the fluid. At the end of the heating season, underground temperatures are commonly around 0℃. In summer, the stored cold can be utilized f or cooling purposes, either via natural cooling or with a reversed heat pump. The resulting waste heat is stored in the underground for use in winter. At the end of the cooling season temperatures can easily reach 16℃. As a result, one also refers to BTES as seasonal storage, having a storage time of roughly 6 months.

- High temperature BTES:

When the overall heat demand in winter strongly exceeds the cooling demand in summer, for instance in greenhouses, or buildings in cold climates, or when high temperatures are required for existing high-temperature supply systems or sanitary hot water systems, one can consider high-temperature storage. By actively loading the underground with heat during summer, for instance by solar collectors, combined heat and power plants, waste heat, etc., the underground can be heated to high temperatures (< 90℃). This heat can be used in winter to provide high-temperature heat, even without additional heat pump. Fig. 58 shows the measured temperatures at a depth of 10 m together with charging and discharging heat loads for such a high temperature BTES coupled to a solar thermal collector installation in Neckarsulm, Germany [14]. It can be seen that during the first five years, the installation was used to heat the boreholes to suitable temperatures, and subsequently a significant portion of the heat charged during summer could be used in winter.

In general, these closed loop systems can be implemented in all types of geology. However, the applicability may be limited by the thermal properties of the underground, drilling issues and hydrogeological properties [15, 16].The thermal characteristics of the underground will play a major role in the storage capacity and power delivery of the BTES set-up. A higher thermal conductivity of the ground will result in an increased extraction rate of heat/cold from the underground. Consequently, the type of underground will have a large impact on the design of the BTES system. Values for thermal conductivities can be consulted in reference [17] or they can be determined by a thermal response test [18, 19]. Concomitant with a high thermal conductivity of the underground, a high conductivity of the borehole itself is desired as well. This can be achieved by using suitable grouting and filling materials, such as betonite or quartz sand.

In addition to the underground characteristics, the storage capacity of a BTES system depends on the installed HVAC equipment, the balance between heat and cold extraction and climate conditions.

The coefficient of performance (COP) of a well designed BTES system is similar to ATES systems, being typically 20-40 for natural cooling, while the heat capacity of the overall BTES system lies between 15-30 kWh/m³. In combination with a heat pump, these installations reach a COP of 4-6 for heating. As with ATES, these systems are among the most energy efficient systems for heating and cooling.

Due to the relatively large amount of boreholes as compared to ATES, the drilling costs of a BTES system are considerably higher which leads to a relatively strong increase in installation costs. Based on several studies, the initial investment for a BTES system (excluding the heat pump) reaches about 800-1200 €/kW [20, 21, 22]. Again, the economical feasibility strongly depends on current energy prices and governmental subsidies. A good implementation of a BTES system leads to a significant decrease in primary energy consumption and greenhouse gas emissions. Studies by the Flemish Institute for Technological Research show that BTES systems used for heating and cooling of buildings may reduce the CO_2 emissions by up to 30% [20, 21, 22].

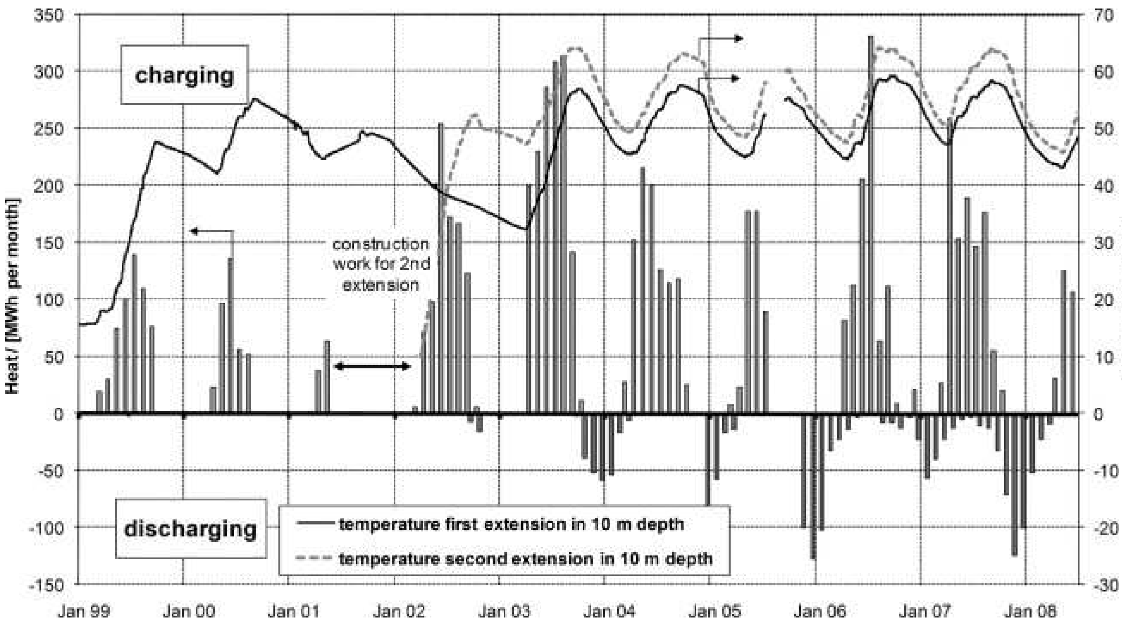


Figure 58. Measured temperatures at a depth of 10 m together with charging and discharging diagrams for the BTES installation in Neckarsulm, DE.[14]

When modelling a BTES system, a first order response model is used to describe the underground heat storage system [23]:

$$mc\dot{x} = \lambda(T_\infty - x) - u \qquad (5.1.3.1)$$

Where x is the temperature of the field, λ the thermal conductivity, T_∞ the undisturbed boundary temperature (*i.e.* the temperature of the ground far away from the field, 274.15 K or 11 °C), m is the mass, c the heat capacity and u the amount of energy extracted per hour.

While mc is a measure of the energy that can be stored and hence should be as large as possible, λ is a measure of the conductivity which needs to be minimized. The combination of a large capacity and small conductivity allows the shifting of large amounts of energy between the heating and cooling season.

Since BTES systems are closed systems, many of the potential risks related to groundwater as described in the ATES section, do not apply. However, in some cases the boreholes penetrate water layers and appropriate measures need to be implemented to prevent mixing and leaking of the groundwater, for instance sealing of the borehole at the interface of the water layer. Thermal pollution is the major source of environmental concerns for BTES systems. In case of a structural imbalance between the heat and cold demand, the underground temperature may change significantly after long term use.

Information of a real case study can be found in the document “Energy performance evaluation of an high temperature borehole thermal energy storage” (Authors: Koen Allaerts, Thomas Nuytten, Johan Van Bael) which is available in the webpage.

6.1.4. Energy pile (thermo-active foundations)

Geothermal heat pump systems have been identified as one of the best sustainable energy technologies for space heating and cooling in buildings. This type of system consists of a sealed loop of pipes buried in the ground, where water or antifreeze flows in order to absorb or dissipate heat into the ground. These loops are connected to a heat pump which "pumps" heat or cold to the building taking advantage of the mild temperature of the soil compared to the air temperature. The wide application of this technology has been hindered by its high initial cost and the land areas required to install the ground heat exchangers.

Geothermal heat exchangers with vertical boreholes are the most frequently used in geothermal heat pumps, because they offer a good performance and require a smaller land area compared with horizontal installation of pipes in trenches, but a lot of land is still needed to drill the boreholes for vertical installation of the geothermal heat exchangers.

The foundation piles of buildings "energy piles" have been used as geothermal heat exchangers in recent years in order to reduce the cost of borehole field and to save land area. Pipes can be buried in concrete piles in configuration of U-tubes or spiral coils.

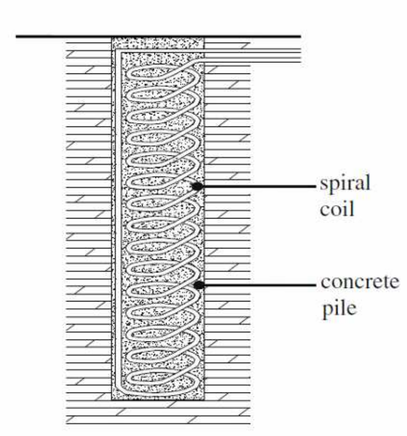


Figure 59. Energy pile

The following is a simplified thermal model that can be used.

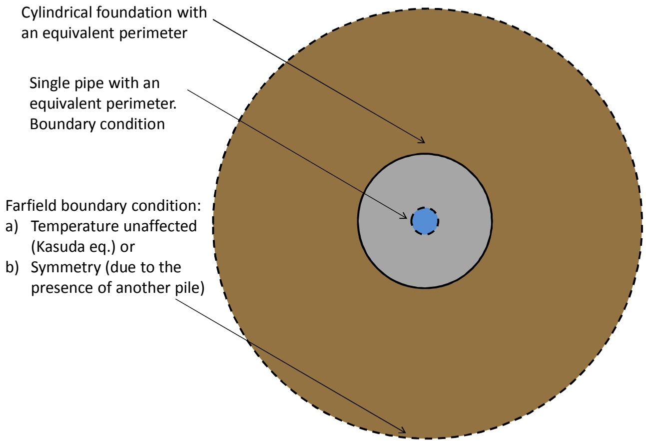


Figure 60. 2-D thermal domain

The domain can be divided in a number of annular surfaces, if the domain was divided in many of these annular surfaces, they would be so thin that it could be considered that the temperature is constant in each of these pieces. The thermal resistance of every annulus could be calculated as follows:

$$R = \frac{\ln\left({r_2}/{r_1}\right)}{2\pi K} \qquad (5.1.4.1)$$

And the energy balance of an annular surface would be

$$\dot{Q}_{in} - \dot{Q}_{out} = \rho\, c_p \pi (r_2^2 - r_1^2)\frac{\Delta T}{\Delta t} \qquad (5.1.4.2)$$

The boundary condition of the inner piping will relate water temperature to the inner part of the foundation by means of the combined thermal resistance of piping and water convection.

The far-field boundary condition depends on the kind of pile that we are simulating. A single energy pile, or a pile located in the perimeter will be able to exchange heat with an undisturbed soil. The characteristic variation time of the soil temperature is one year. For the time τ, the temperature will have an influence (through conduction) on the ground inside a length that is smaller than the following

$$L_{car} = 2\sqrt{\alpha\tau} \qquad (5.1.4.3)$$

The ground far away from the thermal foundation will be mostly undisturbed from a thermal point of view. This region is called the far-field and is used only to set the boundary conditions. The temperature there T (r=L_car, t) can be calculated using the Kasuda equation.

$$T = T_{mean} - T_{amp} * exp\left(-Z\sqrt{\frac{\pi}{365 * \alpha}}\right) * \cos\left(\frac{2\pi}{365} * \left[t_{year} - t_{shift} - \frac{Z}{2} * \sqrt{\frac{365}{\pi * \alpha}}\right]\right) \qquad (5.1.4.4)$$

T = Temperature of soil (ºC)
T_mean = Mean surface temperature (average air temperature). The temperature of the ground at an infinite depth will be this temperature (ºC)
T_ amp = Amplitude of surface temperature (the maximum surface temperature will be T_mean+T_amp and the minimum value will be T_mean-T_amp) (ºC)
Z = Depth below the surface (m)
α = Thermal diffusivity of the ground (soil)
t_year = Current time (day)
t_ shift = Day of the year of the minimum surface temperature (day)

If the pile is located inside a foundation layout its heat exchange is going to be affected by the other piles. In that case the far-field boundary condition should be located at half the distance between piles

$$L_{car} = {}^{1}/_{2}\, L_{piles} \qquad (5.1.4.5)$$

The thermal conditions at the boundary would be symmetry conditions, which means that there is no conduction flux across the symmetry plane and so the normal gradient of temperature is zero at the symmetry plane.

The estimated cost for thermal activation of foundation piles (increase in price of a foundation) is: 20-25 €/m. The estimated cost for thermal activation of foundation slabs (increase in price of a foundation) is: 15-20 €/m2.

The thermal power that a thermal foundation can provide:

- Only heating with a energy pile field (base load operation, annual hours of use ca. 3.000-3.500 h/y) : 15-20 W/m,
- Heating and cooling with a energy pile field (base load operation, annual hours of use heating ca. 3.000-3.500 h/y and (+) cooling ca. 1.000-1.500 h/y) : 30-35 W/m,
- Heating with a activated foundation slab (base load operation, annual hours of use ca. 3.000-3.500 h/y) : 10-15 W/m2 (cooling with a foundation slab is not recommended).

6.1.5. Cavern Thermal Energy Storage (CTES) and solid storage media

Aquifer Thermal Energy Storage (ATES) and Borehole Thermal Energy Storage (BTES) are currently the two most common sensible heat storage techniques. However, the universal applicability of these solutions is limited by two factors [24]:

1. BTES, and particularly ATES, require specific geological conditions
2. Due to the absence of insulation in both these storage techniques, a relatively large heat demand (>100.000 m^3) is imperative for these systems to attain a favorable balance between yield and energy losses.

In Cavern Thermal Energy Storage (CTES), one uses large underground water reservoirs created in the subsoil to serve as thermal energy storage systems. Although this technology is technically feasible, the actual application is limited because of the high level of investment [25]. A noteworthy combination of CTES with geothermal energy recovery was realized in the mine water project of the municipality of Heerlen, NL [26]. Here, an abandoned mine network has flooded forming a huge complex reservoir full of heterogeneities. Using a total of five hot (27-32 ℃), cold (15-18 ° C) and intermediate wells, the district heating system connecting about 300 dwellings and a number of service centers is fed. Additionally, excess heat or cold can be injected through the respective wells for storage in the different temperature zones in the mine.

Several alternatives, which are independent of the characteristics of the underground and are applicable in smaller projects, have been developed. In general, they consist of an insulated container holding water (Hot Water Thermal Energy Storage - HWTES) or a gravel-water mixture (Gravel-Water Thermal Energy Storage - GWTES). The most documented storage installations of this kind are to be found in Germany with storage volumes of up to 12000 m³ heating areas of up to 23.000 m² [14].

– Hot Water Thermal Energy Storage (HWTES):

In this concept, a steel or reinforced concrete tank filled with water as the storage medium, is (partially) built into the ground [see Fig. 61 a)]. Heat insulation is installed around the tank, but sometimes the insulation on the base or even the sides of the tank may be omitted. Thanks to the high heat capacity of water, the capacity of this storage technique is fairly large: between 60 and 80 kWh/m³. The construction often involves stainless steel liner sheets to guarantee water tightness and to reduce heat losses caused by vapor transport through the walls. However, these liners can be quite costly, making smaller installations more expensive (around 500 € / m³). The cost per cubic meter decreases dramatically with increasing size of the tank due to a decreasing A/V ratio, and a value of 120 € / m³ was reached for the 12000 m³ installation in Friedrichshafen, DE [27]. The latter system was able to realize a solar fraction between 21 and 33 %, slightly less than the planned 43 % due to the fact that both energy demand and district heating return temperatures were higher than expected. Nevertheless, the large dimensions of the system resulted in a solar heat cost at analysis date of only 158 € / MWh.

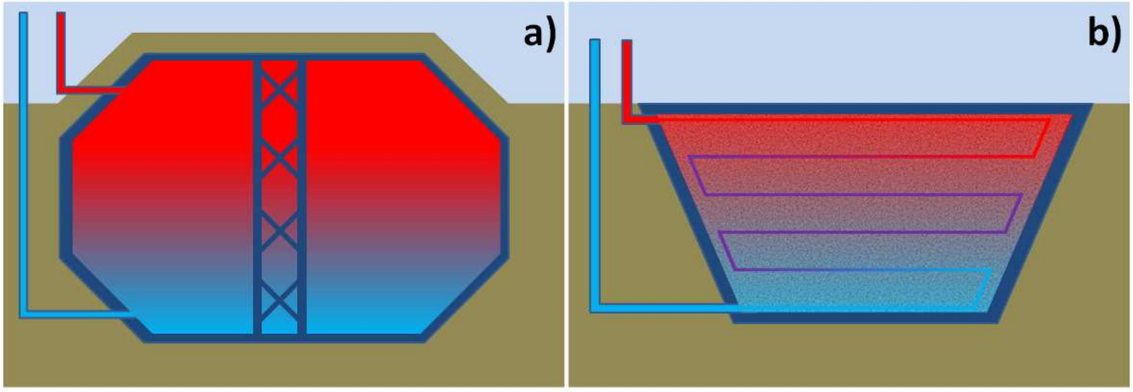


Figure 61: Schematic representation of a HWTES (a) and GWTES (b).

– Gravel-Water Thermal Energy Storage (GWTES):

This somewhat analogous storage concept, sometimes referred to as Pit Thermal Energy Storage (PTES), uses a combination of gravel (pebbles, rocks,...) and water to store seasonal thermal energy that can be inserted or withdrawn by means of a heat exchanger circuit [see Fig. 61 b)] [28]. This technique requires more volume than a HWTES (~1.5 m³ per m³ water-equivalent) [24], but the containing structure, usually in the form of a truncated pyramid, is less expensive and generally more robust, allowing the surface above the storage pit to be available for other, possibly load-bearing purposes. The technique is especially interesting for large volumes and does not require a steel or concrete construction. Gravel filling may be available on-site, making GWTES a very attractive solution both from practical and ecological point of view. Like most seasonal storage installations, GWTES systems become more cost efficient with increasing size, and a projected solar heat cost of 240 € / MWh was reached for the 8000 m³ energy storage facility in Chemnitz, DE [29]. Fig. 62 shows pictures of the different steps in the realization of GWTES seasonal storage in Steinfurt, DE, with a storage volume of 1500 m³ coupled to 510 m² of solar collectors.

As with HWTES, a GWTES installation is often equipped with an integrated heat pump. This allows for lower temperature storage (range between 10 and 80 ℃), significantly reducing the heat losses to the underground and hence improving the efficiency of the seasonal storage system.

Figure 62: Example of a GWTES realization in Steinfurt, DE, with from left to right: excavation of the storage volume, filling of the storage pit with gravel and heat exchanger mesh and fully covered thermal energy storage [24].

Using the appropriate building materials (*e.g.* double-walled modified polypropylene liners and expanded glass insulation for GWTES, reinforced concrete tank for HWTES), storage temperatures of up to 95 ℃ can be reached. When a storage temperature above 100℃ (like in many industrial applications [30]) is necessary, the water storage tank must be able to contain water at its vapor pressure, greatly increasing its cost. At this point, solid storage media such as rocks or pebbles provide, although requiring more space than an equivalent in water, a number of advantages [31]:

1. Rocks are non-toxic, non-flammable and inexpensive
2. Rocks act both as heat transfer surface and storage medium
3. Rock beds combine a large heat transfer area with a low internal heat conductance (limited contact between the rocks), limiting the heat losses from the rock bed.

Occasionally, a combination of rock bed and water storage is proposed. Here, the accumulated solar energy is stored in a water tank, which is surrounded by a rock bed that can serve as additional energy storage medium or as insulation material. An air flow through the rocks can, depending on the design, either preheat fresh air ventilation or meet the entire thermal demand for the building [32]. Alternatively, one can store the solar energy in a rock bed which is surrounded by a water tank. The tank then holds water for domestic hot water purposes, and is heated by the rock bed it surrounds.

6.2. Latent heat – Phase Change Materials

Phase Change Materials (PCM) concern a group of materials capable of storing heat in a phase transition between two states, generally the transition between the solid and the liquid phase. In the ideal case this transition takes place at a fixed temperature but in practice the transition takes place within small temperature range.

To be qualified as a PCM, the energy of the latent heat relates to the phase transition should be higher than the sensible heat in an equivalent volume of water over the same temperature range leading to a lower storage volume.

Water/ice is used as a PCM to store cold at a low phase transition temperature of 0 ºC. It is used in building cooling systems to reduce the required power of the cooling machines and to shift the operation of cooling machines to off-peak periods. Since loading of the cooling storage happens at a lower temperature than the operation temperature of traditional cooling systems (6 – 12 °C) the cooling machine performance (COP) may decrease, what may be compensated by equally lower cold source temperature (for instance the air temperature at night).

PCM's may be used to store heat in two ways:
- In a storage vessel, as a part of the heating or DHW system. Depending on the system function and design, different temperature levels between 25 and 90°C may be useful.
- In the structure of a building, to diminish temperature variation in a building. This requires PCM's operating at 20-25°C.

Application for both purposes is still in the experimental phase.
PCM's for heat storage can be divided into 2 groups on the basis of their chemical characteristics: organic and inorganic PCM's. Table 8 below gives an overview of their general properties.

Table 8. Characteristics of organic and inorganic PCM's

Property	Water/ice	Organic PCM	Inorganic PCM
Example	Water/ice	Paraffin wax 60/63	Sodiumacetate-trihydrate
Phase change	Solid-Liquid	Solid-Liquid (solid-solid possible)	Solid-Liquid
Phase transition temperature	0 °C	Longer trajectory	
Super cooling	-	Generally no supercooling	Shows supercooling Suppressed with additives
Density	1000 kg/m^3		low
Heat capacity	330 kJ/kg		Larger per unit of volume
Aging	No	No	no
Inherent stability	Yes	Yes	No (segregation)
Other characteristics	In most applications up to half of the storage volume is effectively used for phase change, resulting in half the theoretical capacity.	Vaporisation (VOC's) Volume change at transition Flammable Hydrophobic Micro-encapsulation possible	Corrosive No micro-encapsulation

There are several requirements for PCM's that need to be fulfilled in order for the PCM to be applicable.

- Phase transition should lie in the operational range of the system.
- The heat storage capacity (latent heat) of the PCM should be at least as high as alternative media such as sensible heat storage in water.
- Effective thermal conductance during charging and discharging should be sufficiently large to avoid power problems.
- The PCM should be stable during the lifetime of the system (to avoid capacity reduction by aging)
- The PCM should meet legal requirements on flammability and toxicity
- Encapsulated PCM's should guarantee to be chemically inert and strong enough to prevent leaking of the content.
- The price of the PCM should be in conformation with avoided cost for energy and cost reduction of a smaller storage volume per storage unit in comparison with conventional heat storage in water.

Use of PCM without encapsulation is not advised, as use in building materials may lead to sweating of salt hydrates and organic PCM may spread by capillary action. Depending on the molecular weight carbon hydrates may vaporise, this may lead to emission of volatile organic compound (VOC's). Encapsulation is generally based on plastic materials. Micro-capsules are small PCM capsules with diameters of 5-20 µm of hard plastic. The advantage is a relative large surface area for heat exchange and these micro-capsules can be pumped as slurry. Salt hydrates are available only in large capsules (75mm) because of hydrophilic properties. As can be seen from the appendix the temperature range of available PCM's covers the whole range between 0 and 120 °C.

Costs:
A study [33] from 2004 revealed that for large scale application in greenhouses a cost reduction with a factor of 50 was necessary to obtain an economical viable situation with a 5 year span on return of investment. Bulk production of microcapsule PCM's might lead to this situation.

Key performance indicators:
The main key performance indicators are summarized in table 2 below.

Table 9. KPI´s of PCM's

Parameter	Value	Unit	Remarks
Capacity	70-250	kJ/kg	300 kJ/kg is hard to reach at the moment
Capacity	60-300	kJ/l	
power	<0.5	kW/l	the theoretical maximum is about 0.5 kW/l
efficiency		%	similar to water storage, depending on losses
time constant Tau heat losses			similar to water storage, depending on temperature and insulation
Storage time	20	year	for the material itself we calculate with 20 years
temperature range	20-100	°C	
number of cycles	~200	cycles/a	
lifetime -number of cycles	100-100000		depending on material and appliance
costs	18-180	€/kWh	range depending on used materials (no system costs!)

6.3. Chemical heat storage

In chemical heat storage, heat is stored in a reversible chemical reaction, according to:

A(s/l) + heat <=> B(s/l) + C(g)

During charging of the storage, under the influence of heat the material decomposes in two components in an endothermic reaction. These two components can be stored separately, thereby allowing long term heat storage with very low heat loss. On discharging of the storage, the two components are brought in contact, resulting in an exothermic reaction in which the heat is released again.

For chemical heat storage, A and B can be solids or liquids, while C is a gas. In all cases, the storage density depends on the enthalpy change of the reaction, while the reaction temperature depends on the enthalpy change and the entropy change of the reaction, as well as the vapour pressure in the system. At thermal equilibrium, the following equation holds:

$$\Delta G = 0 = \Delta \tilde{H} - T\Delta S + RT \ln p \qquad (5.3.1)$$

ΔH and ΔS for the reaction can be calculated from tabulated values for the formation enthalpy and the specific molar entropy of the reaction components. With these quantities, the equilibrium temperature of the reaction can be calculated.

Absorption in solids

Absorption in solids is characterised by discrete sorption steps in which the vapour is absorbed or desorbed from the solid. As an example, the TGA graph for $CaCl_2x2H_2O$ is shown, showing the stepwise decrease in mass on heating the material due to loss of water vapour, and in addition, a graph is shown with the equilibrium curves for $CaCl_2$ hydrates. From the equilibrium curves, for a given temperature and pressure, the equilibrium state of the material can be found. On crossing an equilibrium curve, the material goes from one hydration state to another, involving a reaction. Note that the equilibrium curves shown end in an open circle, corresponding to the melting point of the material.

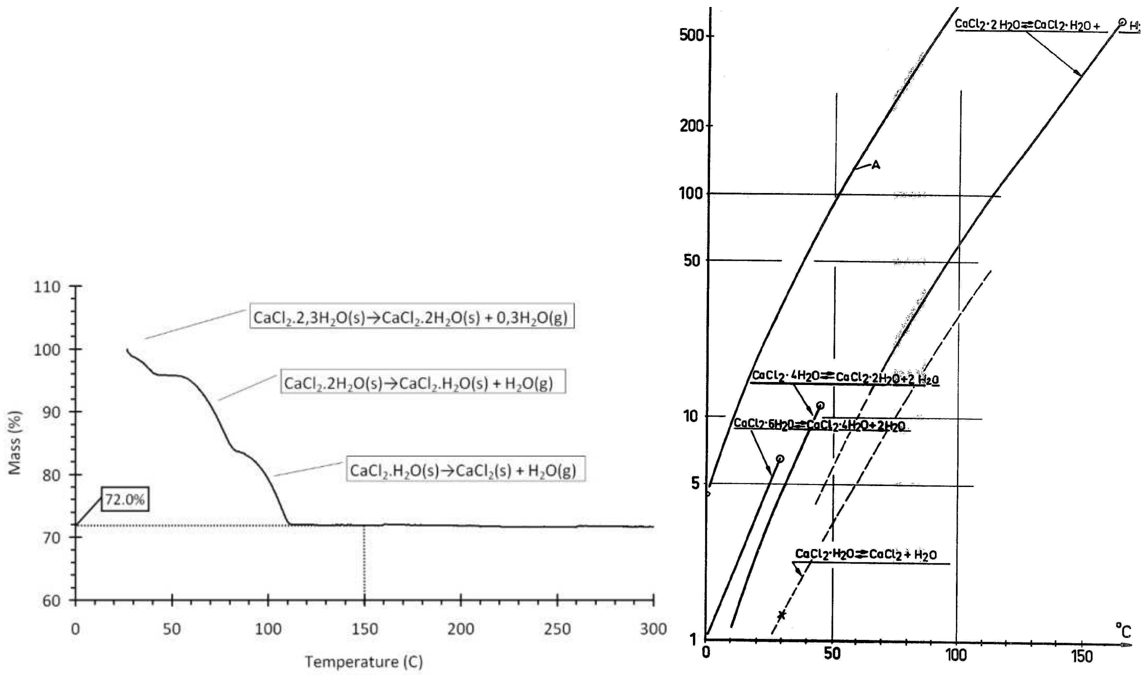


Figure 63. (a) TGA measurements CaCl2x2H2O (Essen, 2010), (b) equilibrium curves CaCl2 hydrates (Brunberg US4186794).

Adsorption in solids

The difference between absorption in solids and adsorption in solids, is that for the latter the vapour is not absorbed into the crystal lattice, but is adsorbed at the (internal) surface of the material. Whereas absorption in the crystal lattice is a discrete process, for adsorption the loading fraction can vary continuously. Below, the isosteres are shown for the water vapour loading of silicagel (the percentages indicating the water loading). However, the isostere plots in an adsorption material can be analysed in the same way as the equilibrium curve plots for an absorption material.

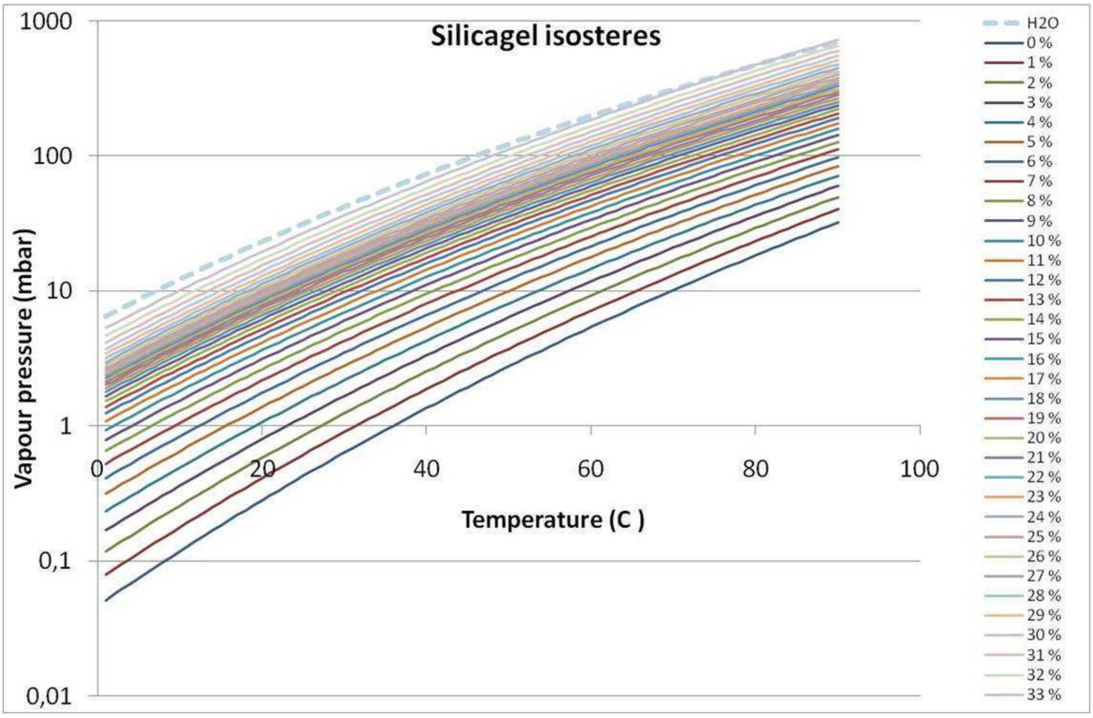


Figure 64. Isosteres for the water vapour loading of silicagel.

Absorption in liquids

Absorption in liquids is very similar to adsorption in solids, in the sense that also here the vapour loading is continuous. Below, the isosteres are shown for an aqueous solution of LiCl.

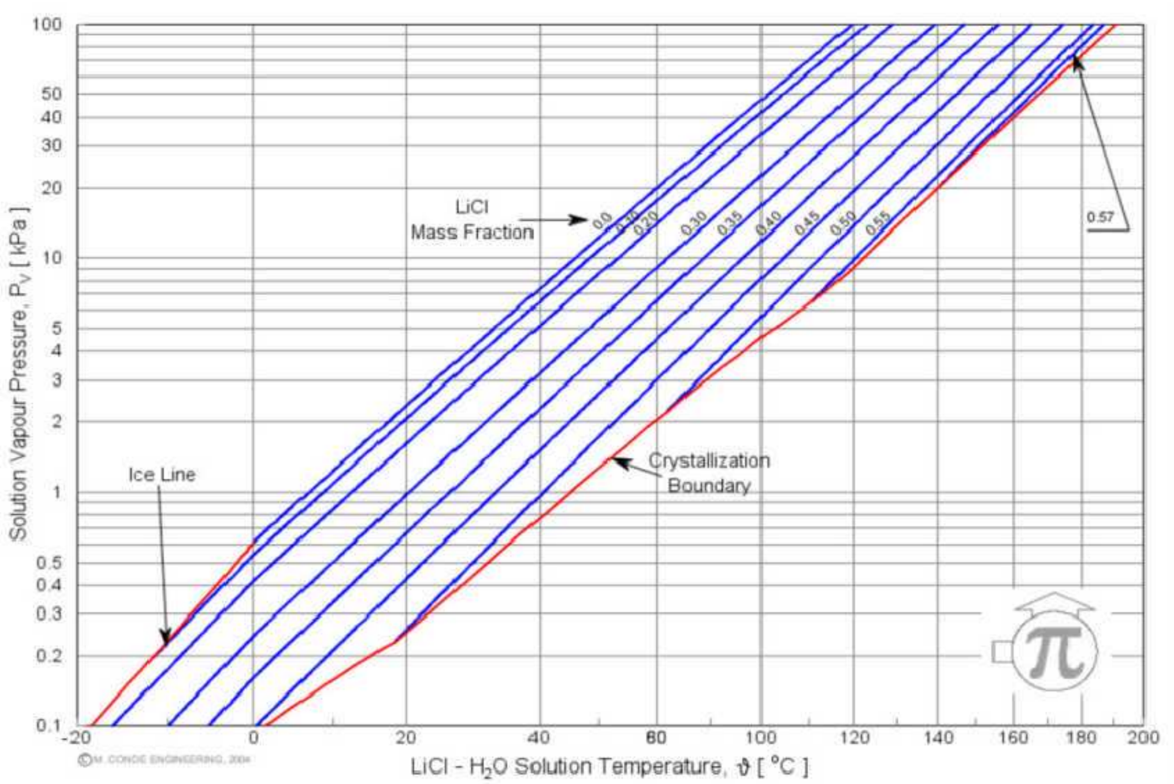


Figure 65. LiCl solution isosteres (Conde, 2008)

Input and Output Temperature

The minimum input- and maximum output temperatures can be found directly from the equilibrium curves, as will be illustrated with the figures above. Figure 1 shows that, for an evaporator temperature of 10℃ , for the liquid water in the evaporator a vapour pressure results of 12 mbar. For this vapour pressure, the same figure shows that the equilibrium temperature for the transition $CaCl_2+H_2O$->$CaCl_2xH_2O$ is about 78℃. Therefore, a temperature step of 68℃ is obtained b etween the evaporator and the $CaCl_2$ bed. However, for the transition $CaCl_2x2H_2O+2H_2O$->$CaCl_2+4H_2O$, the equilibrium temperature for this vapour pressure is about 42℃ (very close to the melting point), resul ting in a temperature step of 32℃ on hydration.

With the same procedure, for a given condenser temperature, the required heating temperature can be found for dehydration of the material. Preferably, to keep the difference between the charging and the discharging temperatures in the sorption bed as small as possible, the condensation temperature and the evaporation temperature should be about the same. For seasonal heat storage, this is best realised by connecting the evaporator/condenser to a borehole, preferably in combination with some heating of the ground, e.g. by means of asphalt collectors.

For liquid solutions, often lower temperature steps are found, especially for low loading fractions. From the isostere curves, for a 30% LiCl solution, a maximum temperature step of about 17℃ is found on hydrati on, and even 45% concentration gives only 30℃. When th e solution is further concentrated, the LiCl deposits in crystalline form.

For adsorption materials, the temperature step that can be obtained with silicagel is very low; if a temperature step over 40℃ is required, only 5% loa ding fraction can be used, resulting in a low energy storage density. For an adsorption materials such as zeolite, the water is more strongly bound than for silicagel, and a much higher temperature step can be obtained, resulting in larger useful loading fractions.

Energy storage density

For the case of vapour sorption by a solid or liquid, the energy storage density depends mainly on the binding enthalpy of the vapour, the required discharge temperature step and the maximum charging temperature step. An overview for a number of thermochemical absorption and adsorption materials is shown below. For an aqueous LiCl solution, the energy density under these conditions would be zero, since the maximum temperature step of the solution is too low

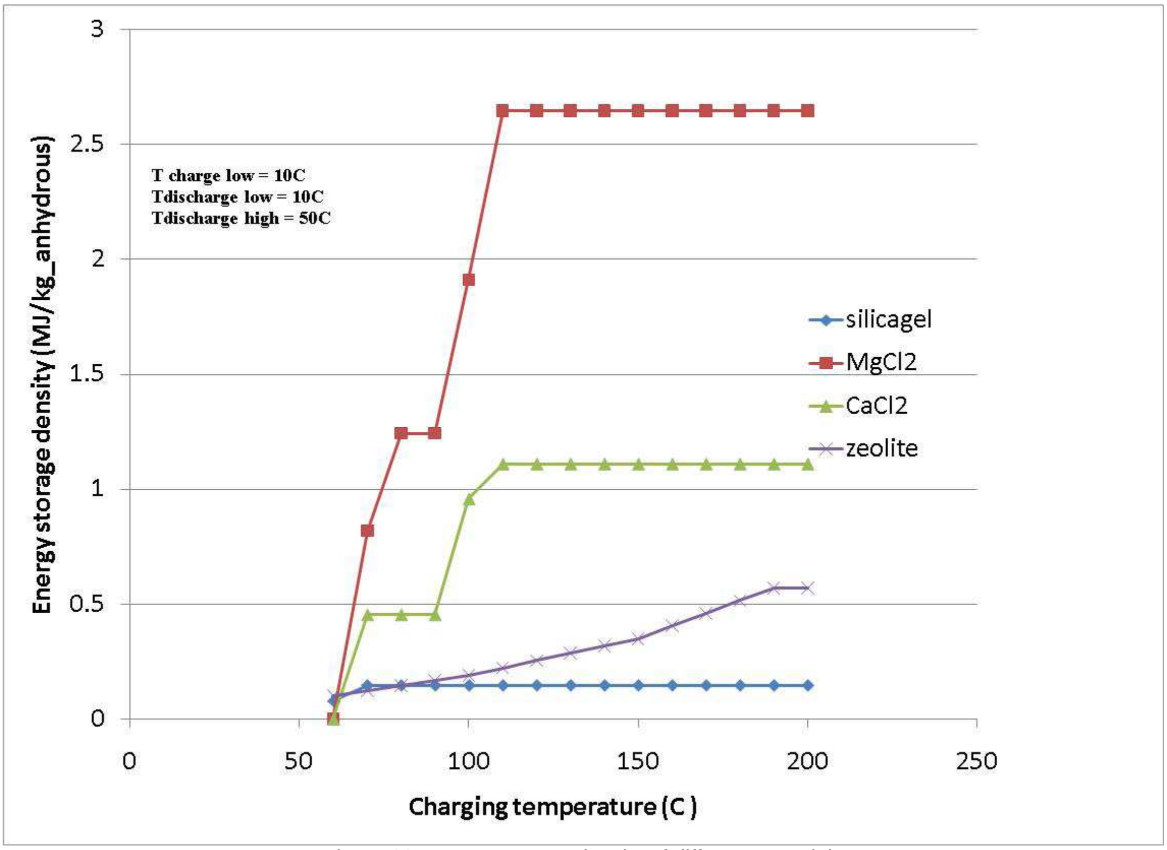


Figure 66. Energy storage density of different materials

For solids, an important issue is the bed porosity that is required for good transport of the vapour through the bed, and that may be as high as 50%, significantly reducing the storage density.

Key performance indicators:

- Capacity (kWh): depends on design; energy density is ~ 1GJ/m3 = 278 kWh/m3.
- Power range (kW): depends on design: no fundamental limit
- efficiency (%): about 80%
- Storage time (month-days-hours; amount): unlimited; for years if required.
- temperature range (ºC): 80-200℃.
- number of cycles: depending on material and system design, at least 100 cycles.
- costs (€/kWh): storage material: 24 euro/kWh (zeolite) to 0.22 euro/kWh ($MgCl_2$).
- equipment cost (€/kW): fan, heat exchangers, other components: to be determined.

7. Electrochemical Energy Storage

7.1. Batteries and Flow Batteries

Batteries consist of single or multiple galvanic cells, connected in series to generate higher voltages. Each such cell consists of two electrodes: the anode, or source of electrons, and the cathode, or sink of electrons, labelled, respectively, as negative and positive in consumer batteries. Whereas the voltage of a cell (E_{cell}) is prescribed by the nature of the chemical reactions at the two electrodes, the power it can deliver, defined as the product of the voltage (E) and the current (I), are governed by much more subtle factors. Some batteries can be used only once, so-called non-rechargeable or primary, and others multiple times, rechargeable or secondary.

Figure 67.Nickel-Cadmium battery

Flow batteries are generally composed by two electrolyte systems in which the two electrolytes, acting as liquid energy carriers, are pumped simultaneously through the two half-cells of the reaction cell separated by a membrane. On charging, the electrical energy supplied causes a chemical reduction reaction in one electrolyte and an oxidation reaction in the other. The thin ion exchange membrane between the half-cells prevents the electrolytes from mixing but allows selected ions to pass through to complete the redox reaction. On discharge the chemical energy contained in the electrolyte is released in the reverse reaction and electrical energy can be drawn from the electrodes. When in use the electrolytes are continuously pumped in a circuit between reactor and storage tanks.

The following tables show the characteristics of each technology:

Table 10. Batteries characteristics (I)

Technology	**Lithium**					**Lead-acid OpzS**	**Zinc Flow Battery**
Formulation	Li-Ion	Li-Ion	LiFeMgPO4	LiFePO4	LiFePO4	PI-H2SO4	Zinc-Bromide
Manufacturer	SAFT	SANYO	Valence	GENASUN	LIFEBATT	FAAM	Premium Power
Model	Intensium Flex	DCB-101	U27-12XP		LIFeBaTT	6OPzS420	Zinc Flow 45
Capacity (Ah)	45	33,6	138	180	15	330	360
Energy (Wh)	2250	1613	1766	---------	2160	594	45000
Life cycles	3000 80%DOD	--------	2000-3000 80% DOD	<2000 80% DOD	2000-3000 80% DOD	500-1000	>4000
Weight (kg)	23	19	19,5	51,5	30	35	1622
Volume (L)	18,58	13,50	12	---------	20,70	16,37	4737
Wh/kg	97,83	84,89	91	---------	72	16,97	27,74
Wh/L	121,09	119,48	148	---------	104,35	36,29	9,50
€/Wh	2,51	--------	0,91	---------	1,41	0,25	1,17

Table 11. Batteries characteristics (II)

Technology	Nickel cadmium			Zebra batteries
Formulation	Ni-Cd (sintered)	Ni-Cd (Pocket plate)	Ni-Cd (Fiber Plate)	NaAlCl4
Manufacturer	SAFT	SAFT	AEGPS	MES-DEA
Model	SPH 52	UP1M75	KFM 120 P	Z37-620-ML3X-32
Capacity (Ah)	48	65	108	32
Energy (Wh)	55	298	247	19840
Life cycles	1500	1500	1500	375 80% DOD
Weight (kg)	2,8	19,6	12	201
Volume (L)	2,04	12,81	8,98	128
Wh/kg	19,54	15,22	20,58	98,71
Wh/L	26,81	23,29	27,49	155
(€/Wh)	1,71	0,92	-----------	0,92

The modelling of the battery follows these equations:

This model takes into account behaviour at very low currents. On discharge (I<0), the formula is:

$$V = V_{oc} - V_{zp} - g_c H + I r_{qc}\left(1 + \frac{m_c H}{Q_c / Q_m - H}\right) \qquad (6.1.1)$$

being:

V - Voltage
V_{oc} - Open circuit voltage at full charge
V_{zp} - Additional voltage term in Hyman model
g_c, g_d - Small-valued coefficients of H in voltage-current-state of charge formulas
H=(1-F) and F - Fractional state of charge = Q/Q_m (l.0 = full charge)
r_{qc} r_{qd} - Internal resistances at full charge when charging; discharging
m_c, m_d - Cell-type parameters which determine the shapes of the I-V-Q characteristics
Q_c,Q_d - Capacity parameters on charge; discharge
Q_m - Rated capacity of cell

and on charge (I>0), it is:

$$V = V_{oc} + V_{zp} - g_c H + I r_{qc}\left(1 + \frac{m_c H}{Q_c / Q_m - H}\right) \qquad (6.1.2)$$

where

$$V_{zp} = \frac{1}{k_{zp}} \ln\left(\frac{|I|}{I_{zp}} + 1\right) \qquad (6.1.3)$$

being:

I_{zp}, K_{zp} - Parameters used in calculating V_{zp}

and

$$V_{oc} = \frac{1}{2}\left(e_{qd} + e_{qc}\right) \qquad (6.1.4)$$

being:
e_{qc}, e_{qd} - Open circuit voltages at full charge, extrapolated from V vs I curves on charge; discharge

To prolong battery life, the battery should not be charged to too high a voltage nor discharged to too low a voltage. The maximum charge voltage limit parameter, V_C, is set below the value at which appreciable gassing of the battery electrolyte commences. If the V_{CONTR} parameter is negative the voltage limit on discharge, V_D is calculated from:

$$V_d = e_d - |I| r_d \qquad (6.1.5)$$

being:
e_d, r_d - Parameters used in calculating V_d

If the V_{CONTR} parameter is >0, then V_D is set to the constant value of V_{CONTR}.

Finally, each mode specifies how the state of charge changes during charge and discharge. In terms of energy (watt-hrs), and

$$V = e_{qc} - g_c H + I\, r_{qc} \left(1 + \frac{m_c H}{Q_c/Q_m - H}\right) \qquad (6.1.6)$$

In terms of charge, Q is the charge (amp-hrs) in the battery, so that

$$\frac{dQ}{dt} = \begin{cases} I & \text{if } I < 0 \\ I * eff & \text{if } I > 0 \end{cases} \qquad (6.1.7)$$

The eff factor is the charging efficiency.

7.2. Hydrogen Storage and generation Systems

The hydrogen storage and generation system is an assembly able to produce hydrogen from electric power, compress and store the gas in pressurised tanks. In case of need (power shortage from the grid or peak consumptions from the users, it is possible to take the stored hydrogen and utilise it in a Fuel Cell (PEM FC or SOFC) and produce power. In this case hydrogen is an energy vector.

In this document we focus on the hydrogen generation through electro dialysis and the hydrogen storage.

The electrolyser is an equipment able to generate gaseous hydrogen (at a pressure level around 10-12 barg or higher) from demineralised water, with the contemporary production of gaseous oxygen in relative small quantities.

Large industrial needs of hydrogen are produced starting from organic materials in large reformers. For small size and high purity hydrogen PEM based electrolysers are more common and commercial.

PEM-based water electrolysis offers a number of advantages for the electrolytic production of hydrogen and oxygen, such as ecological safety, high gas purity (more than 99.99% for hydrogen), the possibility of producing compressed gases (up to 200 bars and more) for direct pressurized storage without additional power inputs, etc. PEM electrolysers are considered as rather attractive devices to accelerate the transition to the hydrogen economy and develop a hydrogen infrastructure network (for example, for the development of re-filling stations for cars, using atomic electric power stations at night hours and also renewable power sources).

Proton exchange Membrane (PEM) fuel cells, also known as Polymer exchange membrane fuel cells typically operate on pure (99.999%) hydrogen fuel. The PEM fuel cell combines the hydrogen fuel with the oxygen from the atmosphere to produce Water, heat (up to 90℃) and electricity.

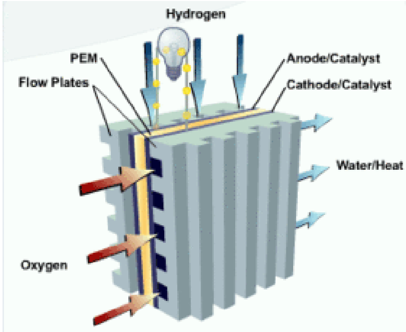


Figure 68. PEM H2 stack

Other kind of electrolyser are alkali electrolyser.

They utilise a water/KOH 30% solution to increase conductivity in the electrolysis cells since demineralised water has practically no conductivity.

Inside the cell the water is consumed, producing H_2 and O_2; the KOH water solution tends to concentrate, then a refill of water is constantly operated to keep the suitable concentration of salt.

The electrolysis stack could be enclosed in a pressure container with suitable oil inside that ease the dissipation of the heat, avoiding possible gas leakage through the stacks.

The electrolyser could be air cooled or water cooled. The heat produced by the electrolyser is dispersed in the environment.

The EL system is usually contained inside a ventilated cabinet, to avoid that any hydrogen leakage can be released close to the equipment. In this way the air contained in the cabinet is collected and discharged in a safe area, far from any source of ignition. The environment inside the cabinet is classified according to ATEX as zone 2.

Hydrogen may be produced at low pressure (3 barg) or at higher pressure (10-30 barg). Water for make-up is pumped at same pressure to enter in the hydrogen generation stack.

After the production of hydrogen, the gas is compressed with a compressor (usually a reciprocating compressor, piston or diaphragm) and stored at high pressure (200 barg or more).

Hydrogen can be fed to Fuel Cell (PEM or any other kind) to produce electric energy.

If we consider:

Power supply to electrolyser: 5.5 kWe
Volume of hydrogen generated: 1 Nm3 (2.77 kWe LHV)
Conversion rate of 1 Nm3 of H2 into the FC to generate electric power = 1.25 kWe/ Nm3 H2

Then, starting from 5.5 kWe (from renewable sources) we can produce (on-demand) 1.25 kWe of electric power.

But we have to consider the compression energy. A membrane compressor for hydrogen is able to compress 5 Nm3/h of gas, consuming 13.5 kWe, i.e. 2.7 kWe/Nm3.

The chain production of H2 / compression / storage / production of power has a rate of :

Rate = 1.25 / (5.5+2.7) = 15,2 %

It means that to have 1 kWe ready “on-demand”, it should “pay” 6.5 kWe from RES, generated when available.

Burning grid power to produce hydrogen is not economical and logical convenient.

Off-grid it is more convenient to store excess of renewable energy (wind or sun) that otherwise is destroyed and utilise the power according to the needs. In any case, this is CO_2-free production of energy, avoiding the transport/shipment of combustible.

The cost per one Nm3/h of gaseous hydrogen delivered at 10-15 barg of pressure is about 12000 €, considering the electrolyser only. Compressor cost is around 15000 € / (Nm3/h).
Hydrogen storage is 60-65 € /Nm3 of gas storage at 200 barg.

If it is defined the PER (primary energy ratio) as simply the ratio between useful energy output divided by the necessary energy input, then input energy is directly kWe from RES and output is the output energy, available from bottle storage.
Considering 1 Nm3 of H_2 (i.e. 2.7 kWe/Nm3), then PER is:

PER = 2.7 / (5.5+2.7) = 33%

Equations describing the system are:

Energy consumption in the EL:

$$P_{EL} = 5.5 * Q_{H2} \qquad Q_{H2} = \text{flowrate H2 (Nm3/h)} \qquad (6.2.1)$$

Water consumption in the EL:

$$Q_w = 1 * Q_{H2} \qquad Q_w = \text{flowrate water (kg/h)} \qquad (6.2.2)$$

Energy consumption in the compressor:

$$P_k = 2.7 * Q_{H2} \qquad P_k = \text{(kWh/Nm3/h)} \qquad (6.2.3)$$

Buffer capacity [J]: this is the number of moles of gas inside the storage vessels, at defined conditions of temperature and pressure and volume. From the moles it is possible to derive the energy [J] applying the conversion rate mole/J. Storage volume is constant. T_{NOM} is the reference temperature (nominal). Pressure can vary according to variation of temperature, then a T_{NOM} shall be defined, pressure shall be compensated according to variation of temperature and after that it is possible to calculate the variation of moles inside the storage vessel.

$$BC_{MAX} = n_{MAX} = (P_1 * V) / (R * T_{NOM}) = (P_2 * V) / (R * T_2) \qquad (6.2.4)$$

Number of moles in the storage is:

$$n = (P_3 * V) / (R * T_{NOM}) = (P_4 * V) / (R * T_4) \qquad (6.2.5)$$

Variation of moles is Δn:

$$\Delta n = n_{MAX} - n = (P_1 - P_3) * \frac{V}{R * T_{NOM}} = \left(\frac{P_2}{T_2} - \frac{P_4}{T_4} \right) * \frac{V}{R} \qquad (6.2.6)$$

Defining SoC_{MIN} as the pressure in the distribution piping (assuming 10 barg), the storage remains filled at 10 barg, since the gas cannot enter the pipeline. In this case SoC of storage vessel is zero (no more gas to the distribution piping).

$$SoC_{MIN} = (P_{MIN} * V) / (R * T) \qquad (6.2.7)$$

where T is the current gas temperature (℃)

State of Charge (SoC) is:

$$SoC = n - SoC_{MIN} \qquad (6.2.8)$$

When $n = n_{MAX}$, $SoC = n_{MAX} - SoC_{MIN} = 1$
When $n = n_{MIN}$, $SoC = n_{MIN} - SoC_{MIN} = 0$

Making substitutions:

$$SoC = (P_4 * V) / (R * T_4) - (P_{MIN} * V) / (R * T) \qquad (6.2.9)$$

If T is current temperature of gas equal to T_4, then:

$$SoC = (P_4 - P_{MIN}) * V / (R * T_4) \qquad (6.2.10)$$

where:
R = gas constant = 0.082 (K * litres * atm / gmole)
P_4 = pressure of gas at T_4 (atm e, absolute)
P_{MIN} is the pressure in the gas distribution piping (atm e, absolute)
T (Kelvin)
V volume in litres

8. Comparison of technologies

8.1. Electricity generation

The following table summarizes all important characteristics of the electric generation technologies.

Table 12. Electric generation technologies

Component type	Efficiency	Power Range	Cost
Photovoltaic			
– Multicrystalline Si	11-15%	Up to 160 W/m^2	2.500-3.000 €/kW (excluding installation costs)
– Monocrystalline Si	10-17%		
– HIT cells	16-17%		
– Ribbon & EFG cells	12-13%		
– α Si (single junction)	4-6%		
– α Si (triple junction)	5-7%		
– CIS	9-11%		
– CdTe	6-9%		
Wind Energy			
Small wind turbines	Expected yield: 150-400 kWh/m^2 year	0,9kW-12kW	2.400-9.100 €/kW
Large wind turbines	Expected yield: 800-1200 kWh/m^2year	0.75 MW – 8MW	1.000 €/KW (land) 2.000 €/KW (sea)
Deep Geothermal	10-17%	20 -120 MW (steam) 1-3 MW (hot water)	800-3.000 US$/kW installed (50% drilling costs)

8.2. Heat generation

The following table summarizes all important characteristics of the thermal generation technologies.

Table 13. Thermal generation technologies for heating[1]

Component type		Efficiency		Power Range	Cost
Boiler		85-95%	PER	Few kW up to large boilers for power generation	< 50 €/kW th
Electric resistance systems		38-40 % [2]	PER	Few kW up to large furnaces	100 €/kW
Solar Thermal	Solar collectors [3]	n/a		0,8-0 kW/m^2	200-1.000 €/kW
	Road Thermal collectors	Thermal performance <30% (based on solar irradiation)		n/a	100-160 €/kW
Heat pump		Electric: 2.5 – 5.0	COP	Few kW up to several MW	240 €/kW
		100 – 200 % [2]	PER		
		Engine: 0.8 – 2.0	PER		
		Thermal: 1.0 -1.8	PER		
Geothermal		Electric: 20	COP	n/a	n/a
		800 % [2]	PER		

1 For DHW, efficiencies are in general 10 – 20% lower due to storage losses (for storage heaters) or start /stop losses (for instantaneous heaters). For heat pumps the COP may be far lower for DHW due to the difference in required temperature level.

2 Efficiency for power generation: 40% (upper calorific value).

3 Solar collectors are in general used for DHW. The performance is depending on collector size and efficiency and solar radiation and is limited by storage volume and DHW use.
For heating the potential solar contribution is in general limited.

8.3. Cogeneration

The following table summarizes all important characteristics of the thermal and electric generation technologies.

Table 14. Thermal and Electric generation technologies

Component type	Efficiency	Power Range	Cost
ORC	<25% (cycle)	Few kW up to 3 MW_e	1.000-2.500 €/kW_e
CHP based on ICE	~80% (overall system)	4-100 kW_e	500 €/kW_e
CHP based on ECE (Steam)	~70% (overall system)	50 kW up to several hundred MW (steam turbines)	> 1.400 €/kW_e installed
CHP based on ECE (Stirling)	65-85% (overall system)	1-10 kW_e	7.000 €/kW installed (Stirling engine)
CHP with STIG and HRSG	32-44% (η_{el})	Few MW up to 51 MW_e	n/a
CHP based on fuell cells and gas reformer	n/a	n/a	n/a
CHP based on hybrid PV/Thermal	Electrical: <conventional module (glazed) =conventional module (unglazed) Thermal: < conventional collector (same size)	Electrical: 160-0 W/m^2 Thermal: 700-0 W/m^2	500-1.000 €/kW

8.4. Cooling generation

The following table summarizes all important characteristics of the cooling generation technologies.

Table 15. Thermal generation technologies for cooling [1]

Component type	Efficiency		Power Range	Cost
Compression chillers (electric or gas engine driven)	3 – 8 Depending on the cold source and emission system (NL)	COP	1 – 1000 kW	370 €/kW th
	88 – 128 % 120 – 320 % (NL) [1]	PER		
Absorption chillers	0.5 – 1.0	COP	n/a	n/a
Free cooling, using ground water (ATES) or ground heat exchangers (BTES) [2]	10 (NL)	COP	1 – 1000 kW	n/a 500 – 750 €/kW th (NL ground heat exchangers)
	400 %	PER		

1 Efficiency for power generation: 40% (upper calorific value). If the compressor is (gas) engine driven, the engine efficiency must be used to asses the PER.

2 Performance indicator relates to cooling power vs pump power of the cold source system.

8.5. Thermal energy storage

The potential differences between the different thermal energy storage systems make it difficult to compare them under the same parameters. Due to that reason, the most important characteristics of each technology are summarized as follows in the next points.

Sensible thermal energy storage:

- Tank storage:
  - Capacity: Few hundred litres up to few thousand m^3
    75-100 litres of storage per m^2 of square area
  - Storage Temperature: Atmospheric pressure <100ºC
    Pressurized tanks slightly > 100ºC

- ATES:
  - Natural groundwater flow: < 30 m/yr
  - Power extraction: 120-2000 kW/pair/10℃
  - Temperature range (cooling): 10/18℃
  - Temperature range (heating): 30/45℃(including the effect of a heat pump)
  - Life span: 20-30 yr
  - Storage power: 30-40 kWh/m^3
  - Cost: 450-900 €/kW
  - Need of energy balance.

- BTES:
  - Natural groundwater flow: < 10-20 m/yr
  - Power extraction: 20-60W/m
  - Temperature range (cooling): 14/18℃
  - Temperature range (heating): 30/45-90℃ (including the effect of a heat pump
  - Life span: 50 yr
  - Storage power: 15-30 kWh/m^3
  - Cost: 800-1200 €/kW
  - Need of energy balance

- Energy pile:
  - Power range: Heating with a energy pile field → 15-20W/m
    Heating and cooling with a energy pile field → 30-35W/m
    Heating with activated foundation slab → 10-15W/m^2
  - Costs: Thermal activation of foundation piles → 20-25€/m
    Thermal activation of foundation slabs → 15-20€/m^2
  - Need of energy balance

- CTES
  - High level of investment
  - Capacities: up to 12.000 m^3 (heating areas up to 23.000 m^2)
  - HWTES: Capacity → 60-80 kWh/m^3
    Cost → 120-500 €/m^3
  - GWTES: Cost → less expensive than HWTES
  - Need of energy balance

Latent thermal energy storage:

- PCM for cold storage water/ice:
  - Capacity: 300 kJ/kg
  - Power range: < 0,5 kW/l
  - Efficiency: similar to water storage, depending on losses
  - Storage time: one – two days
  - Temperature range: 0 ºC
  - Number of cycles: no limit
  - Lifetime-number of cycles: no limit

– PCM for heat storage:
  - Capacity: 70-250kJ/kg // 60-300kJ/l
  - Power range: < 0,5 kW/l
  - Efficiency: similar to water storage, depending on losses
  - Storage time: 20 years
  - Temperature range: 20-100ºC
  - Number of cycles: ~200
  - Lifetime-number of cycles: 100-100.000
  - Costs: 18-180€/kWh

Chemical reactions:

- Energy density: 278 kWh/m^3
- Efficiency: ~80%
- Storage time: unlimited (for years if required)
- Temperature range: 80-200ºC
- Number of cycles: at least 100 cycles
- Costs: From 24€/kWh (zeolite) to 0,22 €/kWh ($MgCl_2$)

8.6. Electrochemical storage

Batteries and flow batteries:

The following table summarizes the main characteristics of the different kinds of batteries and flow batteries.

Table 14. Batteries and flow batteries characteristics

Technology	Lithium	Lead-acid	Zn Flow battery	Ni-Cd	Zebra batteries
Capacity (Ah)	15-180	330	360	48-108	32
Energy (Wh)	1.600-2.250	~600	45.000	55-298	~19.800
Life cycles	From ~2.000 to 3.000	500-1.000	<4.000	1.500	375
Cost (€/Wh)	0,91-2,51	0,25	1,17	0,92-1,71	0,92

Hydrogen storage and generation systems:

- Pressure range (H_2 production): Low pressure (3 barg); High pressure (10-30 barg)
- Storage pressure (H_2): 200 barg or more
- Cost gaseous H_2 at 10-15 barg: ~1.200€ / (Nm^3/h) (electrolyser only)
- Compressor cost: 15.000€/(Nm^3/h)
- Hydrogen storage cost (200 barg, gaseous): 60-65 €/Nm^3

9. Conclusions

Electric generation

Different PV technologies are available; still showing a strong development, resulting in better performance and lower equipment costs. PV can be applied in all scales from a few square meters on a dwelling roof top to hundreds of square meters. The limiting factor is the available, non shaded area.

Wind turbine technology can roughly be divided in three types:

- Small wind turbines (rotor diameter up to ca. 10 m).
  The performance / investment ratio is low, compared to large wind turbines.
- Large land based wind turbines.
  This type currently shows the best performance / investment ratio.
- Large sea based wind turbines.
  This type requires far larger investment than land based turbines.

Large wind turbines have a nominal power of 0,75 MW or more.

Deep geothermal technology is applied for high power productions of 10 MWe or more because of the cost of the installation required.

For an e-hub system it is important to note that power production by PV and wind turbines is climate dependent, so the E-hub system has to handle a situation with fluctuating power production. Perhaps climate forecasting can be used if anticipation is required for optimal control.

For the application of those technologies under the different climate conditions, an exhaustive study of the natural sources in each location has to be done because affects directly to the performance of PV and wind turbine technology.

Heat generation

Under the heat generation technologies, the most promising technologies based on the efficiency and cost are boilers and heat pumps

Boilers have been applied for a long time and are very robust. They can be applied in low (< 50 °C) and high temperature (up to 90 °C) heat delivery systems. Small condensing gas boilers may reach an annual efficiency up to 95 %, using a room thermostat. Using a heating curve control system, small and large (gas) boilers reach an annual efficiency lower than 90 %.

For hot water production instantaneous gas combi-boiler (used for both heating and DHW) reach an annual efficiency up to 80 %. Hot water systems with a storage tank have lower efficiencies due to storage losses.

Gas boilers allow small on-times of 1 – 2 minutes without serious efficiency drop or wear. In combination with the low investment costs, this makes them ideal as a back-up heater in E-hub systems.

Heat pumps have been applied in relatively small numbers over the past ten years. They can only be applied in low (< 50 °C) temperature heat delivery systems or when a high temperature system is operated at low temperatures. Electric heat pumps may reach an efficiency (PER) of 200 %. Auxiliary energy consumption of source pumps or fans may diminish overall performance severely.

For hot water production heat pumps are less interesting due to the performance drop at high temperatures. Electric combi heat pumps may reach an efficiency (PER) of 140 %.

Heat pumps need to be operated with long on-times of minimum 5 minutes to prevent efficiency drop and wear, resulting in a limitation of life span. Due to the high investment costs, heat pumps are almost always operated with an additional back-up heater. The optimal control of this type of systems may be a subject in the E-hub study.

Electric heaters are relative cheap and flexible but suffer from a low PER (40 %) when power generation is taken into account. They may be used as an additional (peak) heater in combination with for instance electric heat pumps, if their share in heat delivery is limited to less than 5 %. An E-hub system should provide the control to minimise the use of this type of additional (peak) heaters.

Solar thermal generation technologies are also interesting, although they do not have high performances and some of them are relatively expensive. The source of primary energy used is the sun (non-costly source) and this is a strong point to make them cost efficient.

The main application is DHW production. In moderate climate zones (Central Europe) half of the annual DHW generation may by done by solar power, with an higher share in Mediterranean area.

Another application may be for heating. In direct application the contribution to heat generation will be small; a seasonal storage system is required to obtain a high result). Solar collectors may also be used to store heat in ATES or BTES to balance the heat and cold demand of these storage systems.

Road thermal collectors can be roughly compared with solar collectors, operating at lower temperatures.

Cogeneration

Different cogeneration techniques are available in a power range starting at 1 kWe. In general, the electrical efficiency is higher for higher nominal powers, resulting in higher overall efficiency.

Cogeneration may be applied and controlled in two ways:

- Heat demand controlled. This is the normal operation of cogeneration applied in dwellings and buildings. So power production is determined by heat demand. For an E-hub system it is necessary to optimise this pattern of power production. If influence on the moment of power production by cogeneration is required, control systems and or heat storage are required to allow a shift in heat demand or generation.
- (Electrical) power demand controlled. This is the normal operation of cogeneration in large power plants, where rest heat or draw-off heat is used in district heating. So heat generation is determined by power production. For an E-hub system it is necessary to optimise the use of the heat. If this requires smoothing of heat demand, control systems and or heat storage are required to allow a shift in heat demand.

In both cases the objective for the E-hub is to maximize the contribution of the cogeneration unit in the heat demand.

Cooling generation

Electric compression chillers are widely applied, using air and water as media at condenser and evaporator. Energy performance is depending on both the chiller quality and temperature levels at condenser and evaporator. The use of low temperature cold sources (ATES, BTES) and high temperature emission systems (12/18 °C in stead of the traditional level 12/6) is required for a high PER.

Gas engine driven compressors are also applied, primarily inspired by limitations of power grids in urban areas, in particular on hot summer days when many (electrically driven) air conditioning systems are operational.

Absorption chillers are little applied, requiring heat (hot water) at a temperature level of 85 °C or more. When rest heat at a relative high temperature level is available, this technique may be relevant.

For E-hub systems the objectives for the cooling function are: minimization of cooling demand, minimization of peak cooling power (using cold storage systems and building heat capacity) and maximization of the cold production by the generators with highest efficiency.

For all cooling generators it’s required to prevent short cycle times and to obtain steady control behaviour.

Thermal energy storage

There are different technologies that can be applied in the E-hub system. Some of them are seasonal storage oriented and others are more oriented to hours - days. For all systems, storage losses are the limiting factor.

Storage systems for DHW are most common, in general as storage for hours up to one day. In combination with solar collectors storage for several days may be interesting. If more flexibility is required in the use of different heat sources, storage volumes increase may be needed. The E-hub system needs control systems to optimise the use of these heat sources and the available storage volume, respecting the minimum storage and temperature demands.

For heating thermal storage systems may be used is different ways:

- Building heat capacity. This may be enlarged by applying PCM materials in the building structure, resulting in a slowly varying building temperature, diminishing the need for heating and cooling. This requires an E-hub system with control systems suitable to handle this behaviour.
- System heat capacity. As a kind of extension of building heat capacity, heat storage systems may be added. An E-hub system needs an optimal control of this storage.
- Seasonal storage requires big volumes, which could be a crucial factor to determine its suitability for the application to the E-hub systems. ATES and BTES systems may be considered as a natural type of seasonal storage, with storage temperatures in general close to the undisturbed soil temperature (± 10°C). PCM and TCM techniques are studied for their potential for seasonal storage. With these techniques and especially TCM, low loss seasonal storage might be possible at different temperatures.

As well as storage time, there are a lot of temperature ranges and also price ranges, which will also influence the selection of the most suitable technologies.

Electrochemical storage

There are differences between the batteries and flow batteries, flow batteries have higher capacities per unit as well as energy and life cycles. The weak point of these technologies could be its price in comparison with other battery technologies.

The hydrogen storage and generation is a rather expensive technology. In addition the efficiency of a complete cycle (electricity into Hydrogen using electrolysis and back into electricity using e.g. a Fuel cell) is low. Nowadays it is only convenient for off-grid applications to use and manage any surplus of renewable energy.

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ANNEXES

Annex A Characteristics of commercially available PCM's

PCM name	type	Tmelt	H	°C	H	density	°C	density	°C	Source	URL
		°C	kJ/kg		kJ/l	kg/l		kg/l			
E117		117	169		245	1.45				EPS Ltd	
RUBITHERM ®RT 100	latent heat paraffin	99	168	91/106	158	0.94	15	0.77	130	*RUBITHERM* GmbH	www.rubitherm.com
RUBITHERM ®RT 90	latent heat paraffin	90	194	82/97	180	0.93	15	0.77	100	*RUBITHERM* GmbH	www.rubitherm.com
E89		89	163		253	1.55				EPS Ltd	
TH89	Salthydrate	89	149		229	1.54				TEAP	www.teappcm.com
RUBITHERM ®PX 80	latent heat powder	77	91	70/85	58	0.64	15			*RUBITHERM* GmbH	www.rubitherm.com
RUBITHERM ®GR 80	latent heat granulate	79	71	71/86	53	0.75	15			*RUBITHERM* GmbH	www.rubitherm.com
RUBITHERM ®FB 80	latent heat fibre board	79	132	71/86	99	0.75	15			*RUBITHERM* GmbH	www.rubitherm.com
RUBITHERM ®RT 80	latent heat paraffin	79	175	71/86	161	0.92	15	0.77	100	*RUBITHERM* GmbH	www.rubitherm.com
PCM72	Salzhydrat/Salz Eutektikum	72	0		290	0				Merck KGaA	
ClimSel C 70		70	194		330	1.7				Climator	www.climator.com
RUBITHERM® RT 65	latent heat paraffin	64	173	56/71	157	0.91	15	0.79	70	*RUBITHERM* GmbH	www.rubitherm.com
ClimSel C 58		58	364	45/75	531	1.46				Climator	www.climator.com
E58		58	226		289	1.28				EPS Ltd	
TH58	Salthydrate	58	226		291	1.29				TEAP	www.teappcm.com
STL55 (Sodiumacetatetrihydrate)	Salthydrate	55	242		312	1.29				Mitsubishi Chemical	
??? (Mitsubishi license)	Salthydrate	55	242		312	1.29				Cristopia	
RUBITHERM® FB 54	latent heat fibre board	55	135	46/61	101	0.75	15			*RUBITHERM* GmbH	www.rubitherm.com

PCM name	type	Tmelt	H	°C	H	density	°C	density	°C	Source	URL
		°C	kJ/kg		kJ/l	kg/l		kg/l			
RUBITHERM ®RT 54	latent heat paraffin	55	179	46/61	161	0.9	15	0.76	70	*RUBITHERM* GmbH	www.rubitherm.com
RUBITHERM® PX 52	latent heat powder	53	103	45/60	66	0.64				*RUBITHERM* GmbH	www.rubitherm.com
STL52 (Sodiumacetatetrihydrate)	Salthydrate	52	201		261	1.3				Mitsubishi Chemical	
E48		48	201		336	1.67				EPS Ltd	
ClimSel C 48		48	324	35/65	441	1.36				Climator	www.climator.com
STL47 (Sodiumacetatetrihydrate eut.)	Salthydrate	47	221		297	1.34				Mitsubishi Chemical	
??? (Mitsubishi license)	Salthydrate	47	221		297	1.34				Cristopia	
RUBITHERM ®RT 42	latent heat paraffin	43	174	36/51	153	0.88	15	0.76	70	*RUBITHERM* GmbH	www.rubitherm.com
RUBITHERM ®GR 41	latent heat granulate	43	63	35/50	47	0.75	15			*RUBITHERM* GmbH	www.rubitherm.com
RUBITHERM ®FB 41	latent heat fibre board	43	117	35/50	88	0.75	15			*RUBITHERM* GmbH	www.rubitherm.com
RUBITHERM ®RT 41	latent heat paraffin	43	152	35/50	134	0.88	15	0.76	70	*RUBITHERM* GmbH	www.rubitherm.com
RUBITHERM ®PX 41	latent heat powder	43	96	35/50	61	0.64	15			*RUBITHERM* GmbH	www.rubitherm.com
RUBITHERM ®RT 36	latent heat paraffin	36	159	27/42	140	0.88	15	0.76	70	*RUBITHERM* GmbH	www.rubitherm.com
RUBITHERM ®RT 35	latent heat paraffin	35	157	27/42	138	0.88	15	0.76	70	*RUBITHERM* GmbH	www.rubitherm.com
ClimSel C 32	Salthydrate	32	302	20/50	438	1.45				Climator	www.climator.com
E32		32	186		272	1.46				EPS Ltd	
RUBITHERM ®RT 32	latent heat paraffin	31	130	23/38	114	0.88	15	0.76	70	*RUBITHERM* GmbH	www.rubitherm.com
E30		30	201		262	1.3				EPS Ltd	
TH29	Salthydrate	29	188		290	1.54				TEAP	www.teappcm.com
RUBITHERM ®RT 27	latent heat paraffin	28	179	19/34	156	0.87	15	0.75	70	*RUBITHERM* GmbH	www.rubitherm.com
RUBITHERM ®GR 27	latent heat granulate	28	72	19/34	54	0.75	15			*RUBITHERM* GmbH	www.rubitherm.com
RUBITHERM ®PX 27	latent heat powder	28	112	19/34	72	0.64	15			*RUBITHERM* GmbH	www.rubitherm.com

PCM name	type	Tmelt °C	H kJ/kg	°C	H kJ/l	density kg/l	°C	density kg/l	°C	Source	URL
A28		28	245		193	0.79				EPS Ltd	
S27	Salthydrate	27	207		304	1.47				Cristopia	
STL27 (Calciumchloride hexahydrate)	Salthydrate	27	213		232	1.09				Mitsubishi Chemical	
RUBITHERM ®RT 26	latent heat paraffin	25	131	15/30	115	0.88	15	0.76	70	*RUBITHERM* GmbH	www.rubitherm.com
ClimSel C 24	Salthydrate	24	216	15/45	320	1.48				Climator	www.climator.com
A22		22	220		171	0.775				EPS Ltd	
RUBITHERM ®RT 20	latent heat paraffin	22	172	nov-26	150	0.87	15	0.75	70	*RUBITHERM* GmbH	www.rubitherm.com
E21		21	150		222	1.48				EPS Ltd	
		20								TEAP	
ClimSel C 15		15	130		0	0				Climator	www.climator.com
E13		13	140		245	1.78				EPS Ltd	
??? (Mitsubishi license)		13	0		0	0				Cristopia	
E10		10	140		213	1.52				EPS Ltd	
??? (Mitsubishi license)		9	0		0	0				Cristopia	
RUBITHERM ®RT 6	latent heat paraffin	8	174	-0.25	150	0.86	-15	0,77/0,73	15/70	*RUBITHERM* GmbH	www.rubitherm.com
E8		8	140		206	1.47				EPS Ltd	
A8		8	220		170	0.77				EPS Ltd	
RUBITHERM ®RT 5	latent heat paraffin	7	156	-0.5	134	0.86	-15	0,77/0,73	15/70	*RUBITHERM* GmbH	www.rubitherm.com
E7		7	120		185	1.54				EPS Ltd	
ClimSel C 7		7	162	0/30	230	1.42				Climator	www.climator.com
TH 7		7	189							TEAP	www.teappcm.com
RUBITHERM ®RT-2	latent heat paraffin	6	214	-10/5	184	0.86	-15	0,77/0,73	15/70	*RUBITHERM* GmbH	www.rubitherm.com
A4		4	227		174	0.766				EPS Ltd	
TH 0		0	334							TEAP	www.teappcm.com

PCM name	type	Tmelt °C	H kJ/kg	°C	H kJ/l	density kg/l	°C	density kg/l	°C	Source	URL
RUBITHERM ®RT-7	latent heat paraffin	-3	165	-15/0	142	0.86	-15	0,77/0,73	15/70	*RUBITHERM* GmbH	www.rubitherm.com
SN03	Saltsolution	-3	328		331	1.01				Cristopia	
STL-3 (sodiumcarbonate sol)	Saltsolution	-3	328		331	1.01				Mitsubishi Chemical	
TH-4		-4	286							TEAP	www.teappcm.com
SN06	Saltsolution	-6	284		304	1.07				Cristopia	
STL-6 (potasiumhydrogencarbonate sol)	Saltsolution	-6	284		304	1.07				Mitsubishi Chemical	
TH-10		-10	283							TEAP	www.teappcm.com
SN10	Saltsolution	-11	310		341	1.11				Cristopia	
STLN10 (Pottasiumchloride solution)	Saltsolution	-11	271		284	1.05				Mitsubishi Chemical	
SN12	Saltsolution	-12	306		324	1.06				Cristopia	
SN15	Saltsolution	-15	311		317	1.02				Cristopia	
STL-16 (ammoniumchloride solution)	Saltsolution	-16	0		0	0				Mitsubishi Chemical	
TH-16		-16	289							TEAP	www.teappcm.com
SN18	Saltsolution	-18	268		324	1.21				Cristopia	
STL-21 (sodiumchloride solution)	Saltsolution	-21	240		269	1.12				Mitsubishi Chemical	
SN21	Saltsolution	-21	240		269	1.12				Cristopia	
TH-21		-21	222							TEAP	www.teappcm.com
SN26	Saltsolution	-26	268		324	1.21				Cristopia	
SN29	Saltsolution	-29	233		268	1.15				Cristopia	
TH-31		-31	131							TEAP	www.teappcm.com
SN33	Saltsolution	-33	245		304	1.24				Cristopia	

Annex B Energy conversion and storage

A) Micro-cogeneration systems:

1. Micro-cogeneration based on internal combustion engines

Cogeneration systems, based on internal combustion engines (ICE), convert mechanical power to electric power while heat is recovered from the exhaust gases, cooling water, and engine oil, to supply thermal energy to the building. This cogeneration system represents the first and most popular choice for small-scale applications thanks to the technology's maturity and high reliability. These systems are available in various sizes, ranging from a few kWe up to higher than 10 MWe. Internal combustion engines having power less than 30 kWe, and adopted for residential cogeneration, are generally based on Otto cycle rather than on Diesel cycle, and they can be fed with several fuels. The most commonly applied fuel is natural gas, but propane, diesel fuel and biogas can be adopted too.

Given the maturity of this technology, with respect to other emerging technologies, the majority of cogeneration systems for residential application are based on internal combustion engines, and currently available on the market at high volumes. The following review provides an overview of commercial products and related major product characteristics.

One limit could be given by the life of the internal engine, with a guarantee up to 2000 h, due to the industrial design and use of the engines. It could be possible to improve the time-life of the ICE, if some parts are protected by wear and tear due to usage with a dedicated design.

1.1 Manufacturer: MARATHON Engine Systems
Website: www.marathonengine.com
Location: USA
Description:

The Ecopower™ cogeneration unit generates both heat and electricity for residential and commercial applications. This system is designed to run inside a residential of building in a clean and quite manner.
Long life Marathon engine can run for 4,000 hours continuously between maintenance needs and is designed to last 10 years before a major overhaul.

It is possible to install multiple units, running in parallel, step by step, optimizing the supply to the request profile.

Manufacturer:		**MARATHON**	
MODEL:		Ecopower	
INPUT:			
Fuel type(s)	-	Natural gas	Propane gas
Flow rate	Nm3/h	31.07 – 67.09 ft^3/h	1.68 – 3.42 ft^3/h
Water IN flowrate	kg/h	-	-
Water temperature IN	°C	-	-
OUTPUT:			
Electric power	kWe	2 – 4.7	2.2 – 4.7
Thermal power	kWt	20,473 – 42,652 BTU	22,520 – 47,088 BTU
Water OUT flow rate	kg/h	-	-
Water temperature OUT	°C		
FEATURES:			
Type of engine	-	Single cylinder, 270 cm^3, 1,700-3,600 rpm	
Type of power output	-		
Electrical efficiency	%	25	25
Global efficiency:	%	>90	92
DIMENSIONS:			
Length	mm	1,400	
Width	mm	800	
Height	mm	1,100	
Weight	kg	390	

1.2 Manufacturer: Energia Nova
Website: www.energianova.it
Location: Italy
Description:
The TANDEM™ (Thermal AND Electrical Machine) cogeneration unit is manufactured by Energia Nova S.r.l. from Turin and runs with a modern internal combustion engine for stationary use with four-stroke Otto-cycle (FIAT FIRE of 1200 cm^3, 8 valves for the 20kWe version and IVECO of 2800 cm^3 with 8 valves for the 50 kWe version), generating both heat and electricity for residential and commercial applications. The gas inlet to the engine is controlled by servo mechanism and the gas used can be methane, GPL or biogas. TANDEM® is the acronym for Thermal AND Electrical Machine and is the natural evolution of the TOTEM project of the 70s, of which the patent is retained by Energia Nova.

FIAT combustion engine - Fire - V8 1.2 CNG KY04 - Type 188A4000

Manufacturer:		**Energia Nova**	
MODEL:		TANDEM FIAT FIRE	IVECO
INPUT:			
Fuel type(s)	-	Natural gas, methane, GPL, biogas	Natural gas, methane, GPL, biogas
Flow rate	Nm3/h	7,4	
Water IN flowrate	kg/h	3600	
Water temperature IN	℃	66,6	
OUTPUT:			
Electric power	kWe	20	50
Thermal power	kWt	44	85
Water OUT flow rate	kg/h		
Water temperature OUT	℃		
FEATURES:			
Type of engine	-	Eight valves, 1200 cm^3, X rpm	Eight valves, 2800 cm^3, X rpm
Type of power output	-		
Electrical efficiency	%	29,03	
Global efficiency:	%	97,01	
DIMENSIONS:			
Length	mm	1600-2200	2110
Width	mm	750	950
Height	mm	1350	1800
Weight	kg	500-750	1450

1.3 Manufacturer: Aisin Seiki Co. Ltd.
Website: www.aisin.com/
Location: Japan
Description:
The specifically designed endothermic engine, manufactured on the basis of TOYOTA's experience, drives a synchronous generator that can supply up to 6 kW of electrical power also when responding the user's needs instantaneously. Aisin Seiki's gas engine cogeneration system produces electricity and sanitary hot water simultaneously by using a gas engine and generator. This system is connectable directly to the main electricity supply line through an inverter, thus achieving a high operating load factor.

Manufacturer:		**Aisin Seiki Co. Ltd.**
MODEL:		6,0 kW Gas Engine CHP Unit
INPUT:		
Fuel type(s)	-	Natural gas, LPG
Flow rate	Nm3/h	(31.07 – 67.09 ft3)
Water IN flowrate	kg/h	-
Water temperature IN	°C	-
OUTPUT:		
Electric power	kWe	6, 240 V, single phase, 2-wire
Thermal power	kWt	11,7
Water OUT flowrate	kg/h	-
Water temperature OUT	°C	Max 65
FEATURES:		
Type of engine	-	Water-cooled vertical 4-cycle 3-cylinder OHV
Type of power output	-	
Electrical efficiency	%	28,8
Global efficiency:	%	85
DIMENSIONS:		
Length	mm	1,100
Width	mm	660
Height	mm	1,500
Weight	kg	465

1.4 Manufacturer: American Honda Motor Co. Inc. e Climate Energy (USA)
Website: www.freewatt.com, www.hondapowerequipment.com
Location: US

Description:
Freewatt® is a product developed in collaboration between Honda and Climate Energy for the U.S. market. Freewatt plus operates using micro-CHP technology, which uses a Honda engine/generator to generate heat, producing electric power as a by product. The Honda unit is paired with a modulating condensing boiler that captures 95% of the available energy.

The MCHP unit, produced by the Honda Motor Company, uses an internal combustion engine to produce both heat and electric power. This unit is an incredibly quiet (only 47 dBA at 1 meter) long life small engine-generator. The engine runs on clean natural gas and can be located in a basement or utility room. This engine produces 1,200 watts of electric power and about 12,000 BTUs per hour of heat for the home.
In addition to being quiet and efficient at generating electric power, the MCHP also has very low pollutant emissions. The engine exhaust passes through a catalytic converter that cleans and cools the combustion products. The low temperature flue gas exhaust from the MCHP can be vented outdoors through inexpensive PVC piping.

Manufacturer:		**American Honda Motor Co. Inc. and Climate Energy (USA)**
MODEL:		Freewatt®
INPUT:		
Fuel type(s)	-	Natural gas, propane
Flow rate	Nm3/h	
Water IN flowrate	kg/h	-
Water temperature IN	℃	-
OUTPUT:		
Electric power	kWe	1,2
Thermal power	kWt	3.46 (12,000 BTU's)
Water OUT flowrate	kg/h	-
Water temperature OUT	℃	
FEATURES:		
Type of engine	-	
Type of power output	-	Electricity and hot water
Electrical efficiency	%	28,8
Global efficiency:	%	89
DIMENSIONS:		
Length	mm	
Width	mm	
Height	mm	
Weight	kg	

1.5 Manufacturer: EC Power
Website: http://www.ecpower.co.uk/
Location: UK
Description:
EC Power has developed two models with XRGI system, one is based on internal combustion engine powered by eight cycle with natural gas and with an output of 15.2 kWe (adjustable to 6 kWe), and the other is based on a Diesel engine with an output of 17 kWe (adjustable to 4 kWe).

Manufacturer:		**EC Power**	
MODEL:		XRGI 15G-TO	XRGI 17D
INPUT:			
Fuel type(s)	-	Natural gas L, LL, H, LPG, propane, butane	
Flow rate	Nm3/h		
Water IN flowrate	kg/h	-	
Water temperature IN	℃	-	
OUTPUT:			
Electric power	kWe	6 - 15.2	4-17
Thermal power	kWt	17-30	11-26
Water OUT flowrate	kg/h	-	
Water temperature OUT	℃		
FEATURES:			
Type of engine	-	4 cylinders	
Type of power output	-		
Electrical efficiency	%	30	35
Global efficiency:	%	92	>85
DIMENSIONS:			
Length	mm	1250	
Width	mm	750	
Height	mm	1110	
Weight	kg	700	

1.6 Manufacturer: Honda Motor Co.
Website: www.honda.com
Location: Japan
Description:
Honda produces a system called ECOWILL cylinder 4 stroke Otto cycle by 163 cm^3, which can be fuelled with natural gas or LPG (Liquefied Petroleum Gas). The engine ECOWILL comes from a partnership between the Japanese Honda and the Osaka Gas company (distribution and sale company of natural gas). The great success of ECOWILL pushed Honda to launch the system also on the US market under the name of Freewatt® (previously detailed).

Manufacturer:		**American Honda Motor Co. Inc. and Climate Energy (USA)**
MODEL:		Natural gas
INPUT:		
Fuel type(s)	-	Natural gas, propane
Flow rate	Nm3/h	(31.07 – 67.09 ft3)
Water IN flowrate	kg/h	-
Water temperature IN	℃	-
OUTPUT:		
Electric power	kWe	1
Thermal power	kWt	3,25
Water OUT flowrate	kg/h	-
Water temperature OUT	℃	Max 75
FEATURES:		
Type of engine	-	One cylinder, 163 cm^3, 1700-3600 rpm
Type of power output	-	Electricity and hot water
Electrical efficiency	%	21
Global efficiency:	%	85
DIMENSIONS:		
Length	mm	
Width	mm	640
Height	mm	940
Weight	kg	257

1.7 Manufacturer: Power Plus Technologies
Website: www.ecopower.de
Location: Germany
Description:
Power Plus Technologies produce a modular system from 1.3 a 4.7 kWe known as Ecopower, which is based on a internal combustion engine produced by the American company Marathon Engine Systems.

Manufacturer:		**American Honda Motor Co. Inc. and Climate Energy (USA)**
MODEL:		Natural gas
INPUT:		
Fuel type(s)	-	Natural gas, propane
Flow rate	Nm3/h	
Water IN flowrate	kg/h	-
Water temperature IN	°C	-
OUTPUT:		
Electric power	kWe	1,3-4,7 (modular)
Thermal power	kWt	4,0-12,5 (modular)
Water OUT flowrate	kg/h	-
Water temperature OUT	°C	
FEATURES:		
Type of engine	-	
Type of power output	-	Electricity and hot water
Electrical efficiency	%	25
Global efficiency:	%	>90
DIMENSIONS:		
Length	mm	1080
Width	mm	740
Height	mm	1370
Weight	Kg	395

1.8 Manufacturer: SenerTec
Website: www.senertec.de
Location: Germany
Description:
The micro-cogeneration system produced by SenerTec DACHS relies on an internal combustion engine cylinder 4 stroke from 579 cm^3, which can be fuelled with natural gas, LPG, oil fuel or biodiesel, and has the following main technical characteristic.

The Dachs has a continuous output of 5.5 kW electricity and 12.5 kW heating and achieves an overall efficiency of circa 90% with a fuel input of 20.6 kW. An additional external exhaust heat exchanger can provide a further 2.5 kW of thermal energy, raising the efficiency up to approx. 98%. In combination with a SenerTec SE 750 buffer vessel, domestic hot water module (capacity 30 litres at 45 °C) and an integrated peak load boiler the so-called Dachs SE solution can meet a heat demand of up to 35 kW.

Manufacturer:		**SenerTec**		
MODEL:		The Dachs G5.5	The Dachs G5.0 Low NOx	The Dachs F5.5 Low NOx
INPUT:				
Fuel type(s)	-	Natural gas	Natural gas	Propane
Flow rate	Nm3/h			
Water IN flowrate	kg/h	-		
Water temperature IN	°C	-		
OUTPUT:				
Electric power	kWe	5,5	5,0	5,5
Thermal power	kWt	12,5	12,3	12,5
Water OUT flowrate	kg/h	-		
Water temperature OUT	°C	83		
FEATURES:				
Type of engine	-	Single-cylinder 4 stroke, 580cc		
Type of power output	-	Electricity and hot water		
Electrical efficiency	%	27	26	27
Global efficiency:	%			
DIMENSIONS:				
Length	mm	1070		
Width	mm	720		
Height	mm	1000		
Weight	kg	530		

1.9 Manufacturer: Tecogen Inc.
Website: www.tecogen.com
Location: US
Description:
Tecogen produces systems for micro-cogeneration of size between 60 and 100 megawatts under the following main features.

Manufacturer:		**Tecogen Inc.**		
MODEL:		Tecogen Cogeneration Modules (Tecogen) CM-60	Tecogen Cogeneration Modules (Tecogen) CM-75	Tecogen Cogeneration Modules (Tecogen) CM-100
INPUT:				
Fuel type(s)	-	Natural gas, LPG		
Flow rate	Nm3/h			
Water IN flowrate	kg/h	-		
Water temperature IN	℃	-		
OUTPUT:				
Electric power	kWe	60	75	100
Thermal power	kWt			
Water OUT flowrate	kg/h	-		
Water temperature OUT	℃	110		
FEATURES:				
Type of engine	-			
Type of power output	-	Electricity and hot water		
Electrical efficiency	%	26	26	29,4-26,1
Global efficiency:	%	83,1-93,7	81,3-91,6	92,5-82,21
DIMENSIONS:				
Length	mm	1,158	1,158	1,219
Width	mm	1,860	1,860	2,134
Height	mm	945	945	1,676
Weight	kg	1,361	1,361	2,041


1.10 Manufacturer: TEDOM
Website: www.tedom.eu
Location: Czech Republic
Description:
In the Czech Republic, TEDOM produces micro-cogeneration systems that are available in different sizes, there are two series:

- TEDOM Cento series (natural gas and biogas) are Combined Heat and Power Units (CHP Units) with an output range from 50 to 400KWe, powered their own heavy duty industrial gaseous fuelled engines. The warm water circuit is modified for a temperature gradient 90/70℃.

- TEDOM Quanto series (natural gas and biogas), has an output from 400 to 2000kW, using heavy duty gaseous fuelled commercial engines.

Manufacturer:		**TEDOM**			
MODEL:		Cento (T80-T100, T120, T160, T180)	Cento (T80-T100, T120, T160, T180)	Quanto (D580, D770, D1200, D1600, D2000)	Quanto (D580, D770, D1200)
INPUT:					
Fuel type(s)	-	Natural gas	Biogas	Natural gas	Biogas
Flow rate	m^3/h	24,2 – 48,9	35,7 – 71,5	151 - 485	218 – 440
Water IN flowrate	kg/h	-			
Water temperature IN	℃	-			
OUTPUT:					
Electric power	kWe	77 - 175	77-175	660-2000	600-1200
Thermal power	kWt				
Water OUT flowrate	kg/h	-			
Water temperature OUT	℃				
FEATURES:					
Type of engine	-				
Type of power output	-	Electricity and hot water	Electricity and hot water	Electricity and hot water	Electricity and hot water
Electrical efficiency	%	33,6 – 37,9	33,2 – 37,6	42,0 – 43,6	42,0 – 42,6
Global efficiency:	%	83,3 – 86,1	81,5 – 85,5	90,4 – 90,9	88,2 – 88,4
DIMENSIONS:					
Length	mm	3700 – 3950			
Width	mm	1485 – 1685			
Height	mm	2380 – 2650			
Weight	kg	4230 - 5100			

1.11 Manufacturer: Yanmar Diesel Engine Co.
Website: www.osakagas.co.jp
Location: Japan

Genelight is a micro-cogeneration system produced by Yanmar Diesel Engine co. in collaboration with Osaka Gas with a power of 5, 6 and 9.9 kWe respectively and with an overall efficiency of 85%.

Manufacturer:		**Yanmar Diesel Engine Co.**		
MODEL:		CP5VB	GECC60A2N	CP-10VB1
INPUT:				
Fuel type(s)	-	Natural gas, propane		
Flow rate	Nm3/h	(31.07 – 67.09 ft3)		
Water IN flowrate	kg/h	-		
Water temperature IN	℃	-		
OUTPUT:				
Electric power	kWe	6		
Thermal power	kWt	11,7		
Water OUT flowrate	kg/h	-		
Water temperature OUT	℃	Max 75		
FEATURES:				
Type of engine	-	One cylinder, 270 cm3, 1700-3600 rpm		
Type of power output	-	Electricity and hot water		
Electrical efficiency	%	29	28,8	31,5
Global efficiency:	%	85	85	85
DIMENSIONS:				
Length	mm	1.100	1.100	1.100
Width	mm	500	660	800
Height	mm	1500	1500	1790
Weight	kg	410	465	790

2.1 Micro-cogeneration based on external combustion engines (steam engines)

An external combustion engine is a heat engine where an (internal) working fluid, high pressure steam in this case, is heated, by combustion of an external source, through the engine wall or a heat exchanger. The fluid then, by expanding and acting on the mechanism of the engine, produces usable work which can be converted to electric power.

Micro-cogeneration systems of this type are generally medium to big size and produce electrical power in the range of 50-1200 kWe, with energy efficiencies ranging from 6-10% up to 12-20% depending on the type of technology applied.

2.1.1 Manufacturer: OTAG
Website: www.otag.de
Location: Germany
Description:
The Lion Powerblock
The system of micro-cogeneration LION ® by Otag is based on a steam engine of small size compared to conventional systems. Its specifications are listed below.

Manufacturer:		**OTAG**
MODEL:		Natural gas
INPUT:		
Fuel type(s)	-	Oil (Gas or pellets)
Flow rate	Nm3/h	
Water IN flowrate	kg/h	-
Water temperature IN	°C	-
OUTPUT:		
Electric power	kWe	0,3 - 2 kW
Thermal power	kWt	3 - 19 kW
Water OUT flowrate	kg/h	-
Water temperature OUT	°C	> 100
FEATURES:		
Type of engine	-	Linator: free-piston steam engine (integrated steam engine with linear power generator)
Type of power output	-	AC
Electrical efficiency	%	-
Global efficiency:	%	>90
DIMENSIONS:		
Length	mm	830
Width	mm	620
Height	mm	1260
Weight	kg	195

2.2 Micro-cogeneration based on external combustion engines (Stirling engines)

Stirling engine provides upper thermal source with external combustion, the inert gas internally expands and condenses, moving the cylinder(s). This movement is transmitted to a power generator. Excess heat is utilized for sanitary water or home heating purposes.

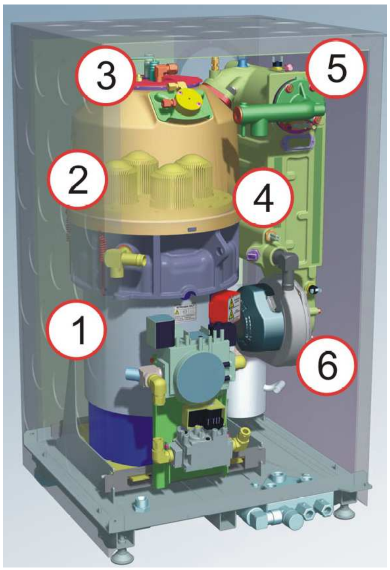
Stirling engines have begun to show market potential since the development of modern free-piston engines. The technology is used in residential cogeneration systems, with the ability to achieve high efficiency, flexibility with regard to fuel, low emissions and low noise levels.

Unlike internal combustion engines, the heat supply is from an external source, allowing the use of different energy sources including fossil fuels (oil or gas) and renewable energy such as solar or biomass. Although it is expected that the electrical efficiency can reach 50%, currently has only reached 40%, while the overall efficiency of a cogeneration system based on a Stirling engine is in the range 65-85%, with a power heat 1.2 to 1.7.

2.2.1 Manufacturer: Whispergen
Website: www.whispergen.com
Location: New Zealand
Description:
The gas-fired WhisperGen™ microCHP system is for home domestic use, acting as an energy efficient boiler heating system that also generates electricity to supplement the grid supply.

Although not designed as a stand-alone or back-up system, the WhisperGen™ microCHP system has already created a quiet revolution in energy generation and is poised to replace boiler systems in many markets. The WhisperGen™ microCHP system provides heating and supplementary power, lowering energy costs, lessening dependence on mass energy production and reducing CO_2 emissions overall.

Manufacturer:		**Whispergen**
MODEL:		microchip System MkVb
INPUT:		
Fuel type(s)	-	Natural gas
Flow rate	Nm3/h	1.55 m3/ hour
Water IN flowrate	kg/h	-
Water temperature IN	℃	-
OUTPUT:		
Electric power	kWe	Max 1
Thermal power	kWt	5.5 - 12
Water OUT flowrate	kg/h	-
Water temperature OUT	℃	75 - 85
FEATURES:		
Type of engine	-	4 cylinder double-acting Stirling cycle
Type of power output	-	AC
Electrical efficiency	%	-
Global efficiency:	%	>90
DIMENSIONS:		
Length	mm	480
Width	mm	560
Height	mm	840
Weight	kg	137



2.2.2 Manufacturer: Stirling Systems
Website: http://stirling-systems.ch/en/start.html

Location: Switzerland and Germany
Description:
The current 1-kw unit which has just successfully finished a two year field test will be complemented by the 9-kW Solo unit.

Their product, Stirling Energy Module (SEM), merges the functionalities of a complete heating burner, the hot water preparation as well as the electric power production for one and multifamily houses.

The device is based on a manifold patented Stirling unit in whose heart electricity is produced completely contact less. The SEM functions in a fully automatic way as conventional boiler (Flow temperature controlled) and warms up the water in the heating-circuit (or in a heat reservoir). Simultaneously it produces electricity that may be used locally or fed into the public grid. Subject to contrary feeding rules, the SEM may be directly plugged into a power socket and thus may be integrated into the electric net very simply.

Manufacturer:		**Stirling Systems**
MODEL:		SEM
INPUT:		
Fuel type(s)	-	Helium
Flow rate	Nm3/h	
Water IN flowrate	kg/h	-
Water temperature IN	°C	650
OUTPUT:		
Electric power	kWe	1,2
Thermal power	kWt	15
Water OUT flowrate	kg/h	-
Water temperature OUT	°C	30-60
FEATURES:		
Type of engine	-	
Type of power output	-	
Electrical efficiency	%	25
Global efficiency:	%	>90
DIMENSIONS:		
Length	mm	
Width	mm	
Height	mm	
Weight	kg	

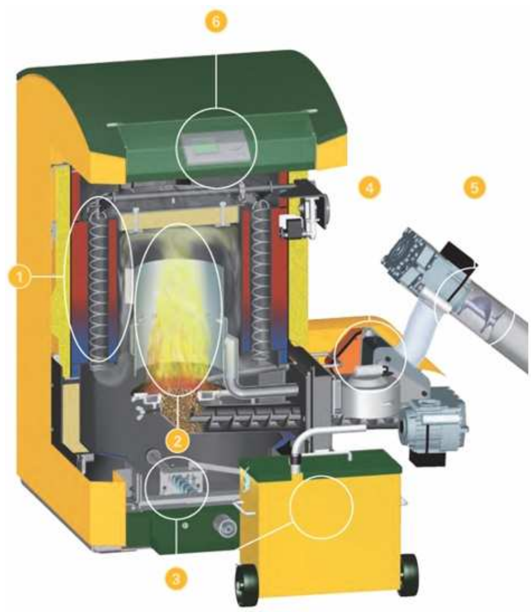
2.2.3 Manufacturer: Stirling Biopower Inc.
Website: http://www.stirlingbiopower.com/STIRLING/BASSE.swf
Location: US
Description:
Stirling Biopower is a privately-owned company, located in Michigan, USA, that designs, tests and manufactures a Stirling engine powered electrical generator called Powerunit^{TM}, which uses a Stirling engine mated to a high voltage induction motor to create a commercial/industrial, electrical generator designed for renewable energy and distributed generation applications. The technology is a breakthrough in the conversion of a wide variety of gaseous fuels and hot air into valuable electric power.

Manufacturer:		**Stirling Biopower**
MODEL:		The PowerUnit^{TM}
INPUT:		
Fuel type(s)	-	Biogas from methane, flare gas, synthetic gas, hydrogen, volatile organic compounds, plus conventional gaseous fuel. Also biomass, liquid fuel, and hot air streams.
Flow rate	Nm3/h	
Water IN flowrate	kg/h	-
Water temperature IN	°C	-
OUTPUT:		
Electric power	kWe	
Thermal power	kWt	
Water OUT flowrate	kg/h	-
Water temperature OUT	°C	
FEATURES:		
Type of engine	-	Four cylinder Stirling engine
Type of power output	-	
Electrical efficiency	%	27-28
Global efficiency:	%	80
DIMENSIONS:		
Length	mm	
Width	mm	
Height	mm	
Weight	kg	

2.2.4 Manufacturer: KWB
Website: www.stirlingpowermodule.com
Location: Austria
Description:

Stirling Power Module has been developed in collaboration with KWB a unit based on Stirling engine powered by wood pellets also called Stirling Power Module.

Manufacturer:		**KWB**
MODEL:		Easyfire 10, 15, 20, 25, 30kW
INPUT:		
Fuel type(s)	-	
Flow rate	Nm3/h	
Water IN flowrate	kg/h	-
Water temperature IN	℃	-
OUTPUT:		
Electric power	kWe	3 – 8.4
Thermal power	kWt	10-30
Water OUT flowrate	kg/h	-
Water temperature OUT	℃	
FEATURES:		
Type of engine	-	
Type of power output	-	
Electrical efficiency	%	-
Global efficiency:	%	91 -94
DIMENSIONS:		
Length	mm	
Width	mm	
Height	mm	
Weight	kg	



2.2.6 Manufacturer: Sunmachine
Website: http://www.pellet-italia.com/doc/SUNMACHINE.pdf
Location: Germany
Description:
Sunmachine produces a Stirling engine biomass, also called the Sunmachine®, capable of producing, depending on the usage that it is from 1.5 to 3 megawatts of electricity and from 4.5 to 10.5 kW of thermal energy. The unit is powered by wood pellets, and has the following technical characteristics.

Manufacturer:		**Sunmachine**
MODEL:		Sunmachine
INPUT:		
Fuel type(s)	-	Wood pellet, solar or biogas
Flow rate	Nm3/h	
Water IN flowrate	kg/h	-
Water temperature IN	℃	-
OUTPUT:		
Electric power	kWe	1,5 - 3
Thermal power	kWt	4,5 – 10,5
Water OUT flowrate	kg/h	-
Water temperature OUT	℃	85
FEATURES:		
Type of engine	-	
Type of power output	-	
Electrical efficiency	%	20-25
Global efficiency:	%	90
DIMENSIONS:		
Length	mm	800
Width	mm	1200
Height	mm	1500
Weight	kg	350

2.2.7 Manufacturer: Sunpower Inc.
Website: www.sunpower.com
Location: US
Description:
For more than 30 years Sunpower, Inc., the originator of free-piston Stirling engines (FPSE), has developed and delivered fully engineered engine prototypes and preproduction units for a variety of applications in aerospace, military, household appliance and research industries.

Sunpower has developed and delivered a variety of free-piston Stirling power generators at power levels ranging from 35 W_e to 7.5 kW_e. Sunpower FPSE units have been demonstrated using a variety of heat inputs including biomass, liquid and gaseous fossil fuel burners, solar concentrators and heat pipes. Here are the technical specifications of the model EG-1000 size 1 kWe.

Manufacturer:		**Sunpower Inc.**		
MODEL:		EG-1000 FPSE	EE-35 FPSE	EE-80 FPSE
INPUT:				
Fuel type(s)	-	Natural gas		
Flow rate	Nm3/h			
Water IN flowrate	kg/h	-		
Water temperature IN	℃	-		
OUTPUT:				
Electric power	kWe	1	0,43	0,86
Thermal power	kWt	32		
Water OUT flowrate	kg/h	-		
Water temperature OUT	℃			
FEATURES:				
Type of engine	-			
Type of power output	-			
Electrical efficiency	%	-		
Global efficiency:	%	90		
DIMENSIONS:				
Length	mm			
Width	mm	270		
Height	mm	435		
Weight	kg	35		

2.2.8 Manufacturer: WhisperTech Limited
Website: www.whispergen.com
Location: New Zealand
Description:
WhisperTech Limited has developed two cogeneration units, which produce respectively DC and AC electrical current. The AC is fuelled by natural gas or oil and is designed primarily for residential urban or remote applications, possibly connected to the electricity grid.

Manufacturer:		WhisperTech Limited	
MODEL:		WhisperGen™ MkV AC Gas-fired	12V/24V DC Diesel
INPUT:			
Fuel type(s)	-	2H and 2nd family natural gas	Automotive grade diesel
Flow rate	Nm3/h		
Water IN flowrate	kg/h	-	
Water temperature IN	°C	-	
OUTPUT:			
Electric power	kWe	1	0,8
Thermal power	kWt	7,5 – 1,2 (modulated)	5.5 (modulated)
Water OUT flowrate	kg/h	-	
Water temperature OUT	°C		
FEATURES:			
Type of engine	-	4 engine double acting Stirling cycle	4 engine double acting Stirling cycle
Type of power output	-	AC	DC
Electrical efficiency	%	-	
Global efficiency:	%		
DIMENSIONS:			
Length	mm	560	500
Width	mm	480	450
Height	mm	840	650
Weight	kg	137	90

3.0 Micro-cogeneration based on Fuel Cells

This technology allows producing electrical energy at high efficiency and with very low emissions in comparison to other cogeneration systems. In stationary applications such as cogeneration, fuel cells can provide electric efficiency in a range from 30% to 60% with global efficiencies from 70% to 90%. Main advantages of CHP systems based on fuel cells are reduction of noise, clean combustion, very low maintenance requirements and potential to reach very high efficiency also in small power plants. To date, their principal limitations are represented by the high costs and their relatively low lifetime. Currently, several researches are performed in order to develop cheaper materials and to improve mass production processes thus to reduce overall fuel cell costs.

3.1 Manufacturer: Acumentrics Corporation
Website: www.acumentrics.com
Location: USA
Description:
Acumentrics produces cogeneration systems based on solid oxides fuel cells for industrial and commercial applications, having sizes of 2 up to 100 kWe. Moreover, they have designed two plants for residential applications, RP-SOFC-5.000 and RP-SOFC-10.000, which provide 5 and 10 kWe respectively. These plants are based on a patent technology that allows direct injection of different fuels and produces negligible NOx e SOx emissions. The unit of 10 kWe is provided with heat exchangers to supply sanitary water.

Manufacturer:		**Acumentrics**
MODEL:		CP-SOFC-10000
INPUT:		
Fuel type(s)	-	Natural gas, methane (standard) Propane, ethanol, methanol, and hydrogen (optional)
Flow rate	Nm3/h	
Water IN flowrate	kg/h	
Water temperature IN	℃	
OUTPUT:		
Electric power	kWe	10
Thermal power	kWt	4
Water OUT flowrate	kg/h	
Water temperature OUT	℃	
FEATURES:		
Type of engine	-	SOFC
Type of power output	-	AC
Electrical efficiency	%	40-50
Global efficiency:	%	75
DIMENSIONS:		
Length	mm	1727
Width	mm	14
Height	mm	1829
Weight	kg	680

3.2 Manufacturer: Ballard Power Systems Inc. and Ebara Ballard Corporation
Website: www.ballard.com
Location: Canada and Japan
Description:
Ballard Power Systems is the world leader in the development, production and sale of PEM (Proton Exchange Membrane) fuel cells for portable applications, stationary and automotive. For the Japanese market, the Japanese joint venture between Ballard Power Systems, Canada, and Japan, Ebara Corporation, led to the creation of Ebara Ballard Corporation. Currently Ebara Ballard, in collaboration with Osaka Gas and Nippon Oil, is working on a cogeneration unit 1 kWe, Mark1030 ™, powered by natural gas, destined for the Japanese market.

Manufacturer:		Ballard
MODEL:		FCgen-1030
INPUT:		
Fuel type(s)	-	Hydrogen or reformate
Flow rate	Nm3/h	
Water IN flowrate	kg/h	
Water temperature IN	℃	50-60
OUTPUT:		
Electric power	kWe	1.2
Thermal power	kWt	
Water OUT flowrate	kg/h	
Water temperature OUT	℃	
FEATURES:		
Type of engine	-	
Type of power output	-	
Electrical efficiency	%	
Global efficiency:	%	54-63
DIMENSIONS:		
Length	mm	347
Width	mm	158
Height	mm	259
Weight	kg	12

3.3 Manufacturer: Ceramic Fuel Cells Ltd.
Website: www.cfcl.com.au http://www.bluegen.info/en/bluegen/technology/technical-data/
Location: Australia and Germany
Description:
Ceramic Fuel Cells is an Australian company that develops solid oxide fuel cell (SOFC) technology to provide reliable, energy efficient, high quality, and low-emission electricity from widely available natural gas and renewable fuels. CFCL is developing SOFC products for small-scale on-site micro combined heat and power (m-CHP) and distributed generation units that co-generate electricity and heat for domestic use.

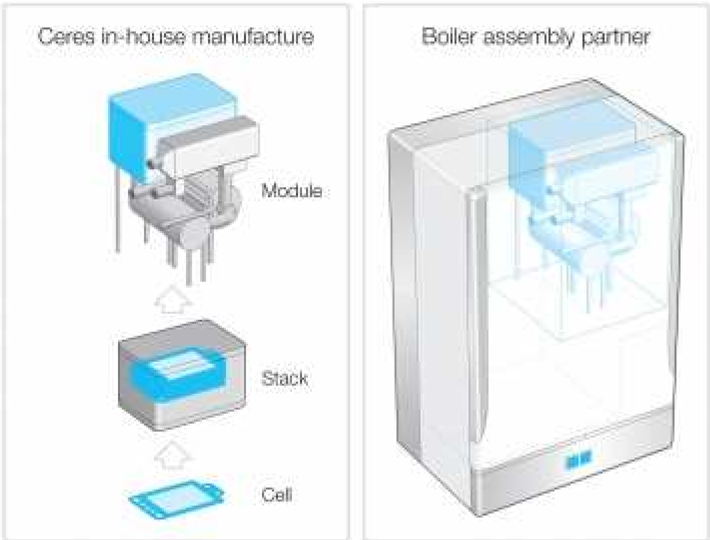
BlueGen™ is a modular, fuel cell generator for distributed electricity generation. Operating on natural gas, BlueGen™ delivers a world leading 60 percent electrical efficiency in small scale generation. BlueGen™ has the ability to recover heat from the fuel cell for hot water - which increases the total efficiency up to 85 percent.

Gennex™ is a 1kW fuel cell module which is designed for integration inside the appliances of tomorrow. Gennex is ideally suited for micro-Combined Heat and Power (micro-CHP) appliances such as high efficiency condensing boilers, heat pumps and air circulation systems. Appliance manufacturers can 'integrate' the Gennex fuel cell module into their products by 'sharing' common inputs and outputs from the fuel cell - for example; natural gas, water, heat and electricity.

Manufacturer:		Ceramic Fuel Cells Ltd.	
MODEL:		BlueGen™	Gennex
INPUT:			
Fuel type(s)	-	Natural gas	Natural gas
Flow rate	Nm3/h	12.6 MJ/hr	
Water IN flowrate	kg/h		
Water temperature IN	°C	50-60	
OUTPUT:			
Electric power	kWe	0,2	2
Thermal power	kWt	0,3	1
Water OUT flowrate	kg/h		
Water temperature OUT	°C		
FEATURES:			
Type of engine	-		
Type of power output	-		
Electrical efficiency	%	60	57
Global efficiency:	%	85	85
DIMENSIONS:			
Length	mm		432
Width	mm		432
Height	mm		815
Weight	kg		

3.4 Manufacturer: Ceres Power
Website: www.cerespower.com
Location: UK
Description:
Ceres has developed a unique adaptation of Solid Oxide Fuel Cell (SOFC) technology, able to operate at temperatures substantially lower than conventional designs which typically run at 800 - 1000 degrees C. By using a new generation of ceramic materials known as CGO (cerium gadolinium oxide) instead of the industry standard YSZ (yttria stabilised zirconia), operation at 500 - 600 degrees becomes possible.

The Ceres CHP product is designed to generate all of the heating and hot water and the majority of the electricity needed by a typical UK home. Ceres Power's unique fuel cell technology enables the product to match daily and seasonal energy demands all year round, substantially reducing the need to buy electricity from the mains power grid.



3.5 Manufacturer: Ebara Corporation
Website: http://www.ebara.co.jp/en/
Location: Japan
Description:
Ebara Corporation participates together with name Eneos Celltech co. Ltd., Matsushita Electric Industrial Co. Ltd., Toshiba's Fuel Cell Power Systems Corporation and Toyota Motor Corporation – a project of large-scale experimentation, whose objective is to accelerate the commercialization of fuel cells in various sites in Japan.

Manufacturer:		Ebara Corporation
MODEL:		
INPUT:		
Fuel type(s)	-	
Flow rate	Nm3/h	
Water IN flowrate	kg/h	
Water temperature IN	℃	
OUTPUT:		
Electric power	kWe	1
Thermal power	kWt	
Water OUT flowrate	kg/h	
Water temperature OUT	℃	
FEATURES:		
Type of engine	-	
Type of power output	-	
Electrical efficiency	%	50
Global efficiency:	%	
DIMENSIONS:		
Length	mm	800
Width	mm	350
Height	mm	900
Weight	kg	150

3.6 Manufacturer: Electrocell Group
Website: http://www.electrocell.com.br/
Location: Brazil
Description:
Electrocell was formed by a group of entrepreneurs in 1998, with multitechnical experience, which joined efforts to develop technology related to fuel cells. Today the company is located at the Technological Park of CIETEC in Sao Paulo, the largest technology centre of Brazil.

Electrocell focuses on energy generation through PEM Fuel Cells and related equipment, peripherals, accessories and services. The Fuel Cell converts chemical energy directly to electrical and thermal energy, providing continuous operation as long as hydrogen is available. Hydrogen can be purchased on the market or produced on site from sources such as natural gas, ethanol or biomass. This noiseless and pollution-free technology creates sustainable, clean and high quality energy.

Electrocell's main products are ECOGEM stationary PEM fuel cell systems from 1kW to 50kW with technology developed 100% in-house; fuel cell test equipment to US or EU standards; PEM fuel cell components, such as bipolar plates, MEA's and sealing; electronic loads from 5W to 5kW for tests and simulation of electrical loads, inverters, gas control panels for monitoring systems and fuel cell diagnosis. Another important, related line is bipolar batteries for electric vehicles, photovoltaic generation and other applications.

3.7 Manufacturer: Eneos Celltech Corporation
Website: http://www.eneoscelltech.co.jp/index.html http://www.ene-farm.info/en/products/index.html
Location: Japan
Description:
Eneos Celltech, a joint company with Sanyo Electric Company for stationary fuel cells. It produces ENE-FARM fuel cell co-generation systems for home use. The co-generation system offers the functionality of fuel cells in a compact and easy to use form, and can even provide you with hot water from the heat it generates producing power. This amazing energy system is the ENE-FARM household-use fuel cell co-generation system.

Manufacturer:		Eneos Celltech Corporation	
MODEL:		ENE FARM 191-TB01	191-ES01
INPUT:			
Fuel type(s)	-	City Gas 13A	City Gas 13A
Flow rate	Nm3/h		
Water IN flowrate	kg/h		
Water temperature IN	℃		
OUTPUT:			
Electric power	kWe	700 to 250W	
Thermal power	kWt	900 to 250W	
Water OUT flowrate	kg/h		
Water temperature OUT	℃		
FEATURES:			
Type of engine	-	3 wire single phase 100/200V (50Hz/60Hz)	3 wire single phase 100/200V (50Hz/60Hz)
Type of power output	-	Electricity	
Electrical efficiency	%	50	
Global efficiency:	%	72-80	
DIMENSIONS:			
Length	mm	890	900
Width	mm	300	350
Height	mm	895	900
Weight	kg	105	105

3.8 Manufacturer: Baxi Innotech
Website: http://www.baxi-innotech.de/
Location: Germany
Description:
The GAMMA 1.0 can perform to its best advantage in combination with a separate heat storage unit and a sophisticated control system – to provide heat that meets all demands conveniently. The advantages of the energy manager operation system make it extremely easy to use in conjunction with its home energy management facility.

Manufacturer:		Baxi Innotech
MODEL:		GAMMA1.0 (low- temperature PEM fuel cell)
INPUT:		
Fuel type(s)	-	Natural gas, biogas
Flow rate	Nm3/h	
Water IN flowrate	kg/h	
Water temperature IN	℃	
OUTPUT:		
Electric power	kWe	1
Thermal power	kWt	1,7
Water OUT flowrate	kg/h	
Water temperature OUT	℃	
FEATURES:		
Type of engine	-	
Type of power output	-	
Electrical efficiency	%	32
Global efficiency:	%	96
DIMENSIONS:		
Length	mm	1600
Width	mm	600
Height	mm	600
Weight	kg	200

3.9 Manufacturer: Fuji Electric
Website: http://www.fujielectric.com/index.html
Location: Japan
Description:
One of the company's core fields includes environment technologies, where Fuji develops new businesses such as energy-conservation, new-energy utilization, waste treatment facilities, refuse-derived fuel (RDF) power generation and advanced water treatment systems by restructuring existing environment-related operations.

The company is also involved in developing residential fuel cell application in a range of 1-5kW and is taking part in the Japan Gas Association (JGA) demonstration project, a programme which aims to commercialise small stationary fuel cells in Japan. Previously, Fuji has been focusing on PAFC but has now changed its efforts towards PEM units and has increased 1kW stack run-time to more than 15,000 hours.

3.10 Manufacturer: Helion Hydrogen Power under the Areva Group
Website: http://www.helion-hydrogen.com/indexuk.php
Location: France
Description:
HELION devotes a large part of its R&D in the area of PEM fuel cell technologies in collaboration with its partners. Development covers the improving of the following key points:

- the performance of key components in both stack and system
- the operating and ageing mechanisms

The objective aimed for is a perfect mastery of the technologies, large reductions in weight and volume, an increase in the durability of systems and significant reduction of costs.

Over the last 4 years, stacks have seen their costs reduced by a factor of 4 to 5 while their power has increased by a factor of 10, rising from 5 kWe in 2003 to more than 60 kWe at present.

3.11 Manufacturer: Ida Tech
Website: http://www.idatech.com/
Location: US
Description:

IdaTech's ElectraGen fuel cell systems provide extended run backup power to mobile network sites when there is loss of electrical power due to severe weather conditions or limited grid capacity. In addition to backup power, IdaTech is also developing prime power systems to provide the primary source of energy for off-grid sites. Their fuel cell products are a direct replacement to traditional power generators and provide our customers economic and environmental benefits. IdaTech is commercializing fuel cell systems as an alternative and sustainable energy for telecommunication companies lowering their greenhouse emissions and carbon footprint.

- The ElectraGen™ H2-I System is a backup power fuel cell system, available in 2.5 kW and 5 kW configurations. These systems provide reliable backup power for telecommunications applications. ElectraGen™ H2-I System operates on hydrogen, providing a clean technology with zero emissions and low environmental impact. It utilizes advanced proton exchange membrane (PEM) technology and is designed for critical backup power applications where performance, low maintenance and long service life are required.
- The ElectraGen™ ME System is an extended run backup power fuel cell system, available in 2.5 kW and 5 kW configurations. These systems provide reliable backup power for telecommunications applications. It includes a fuel reformer that converts methanol and water liquid fuel into hydrogen gas to power the unit. By generating its own hydrogen, the need for delivery and storage of bottled hydrogen is eliminated. The system is designed for reliability, long autonomy and minimal maintenance.

Manufacturer:		Ida Tech	
MODEL:		ElectraGen H2-I System	ElectraGen ME System
INPUT:			
Fuel type(s)	-	Hydrogen	Hydroplus (methanol-water)
Flow rate	Nm3/h		
Water IN flowrate	kg/h		
Water temperature IN	℃		
OUTPUT:			
Electric power	kWe	2.5 or 5	2.5 or 5
Thermal power	kWt		
Water OUT flowrate	kg/h		
Water temperature OUT	℃		
FEATURES:			
Type of engine	-		
Type of power output	-		
Electrical efficiency	%		
Global efficiency:	%		
DIMENSIONS:			
Length	mm	1080	1350
Width	mm	920	1150
Height	mm	1250	1760
Weight	kg	158	295

3.12 Manufacturer: IHI (Ishikawajima-Harima Heavy Industries)
Website: http://www.ihi.co.jp/en/index.html
Location: Japan
Description:
Ishikawajima-Harima Heavy Industries participates in the development of fuel cells, cogeneration and coal gasification combined power generation. The company has started the automatic operation tests on propane gas reformers for home use 1 kW PEMFC systems. Furthermore, IHI has developed a 5kW PEM unit powered with city gas which aims to be sold as a commercial power back-up unit.

3.13 Manufacturer: Intelligent Energy
Website: http://www.intelligent-energy.com/
Location: UK
Description:
Intelligent Energy is a leading clean power systems company focused on a cleaner, lower carbon and more efficient energy future. Intelligent Energy is a global company located in the UK, and the US, with offices in Japan and India.

They produce the most advanced PEM (proton exchange membrane) fuel cell stack technologies available and each features class-leading power densities and robust metallic construction, novel cooling and water management, plus proven durability lifetime test performance. Their PEM fuel cell technologies are unique and not simply a derivative of the conventional stack architectures that have been widely adopted by many companies in the fuel cell sector.

Integrated humidification and innovative cooling (without the need for secondary coolant circuits or external humidification) reduces the component count within the stack, and eliminates much of the conventional balance of plant, resulting in power generation system that are compact and highly reliable- tested over many thousands of hours of operation.

Full power can be achieved from our systems almost instantaneously at room temperature, and our 7 series power systems for example take less than 60 seconds at $-25^{o}C$. Intelligent Energy has successfully started such systems from as low as $-40^{o}C$ and continues to improve and innovate in this area.

3.14 Manufacturer: Panasonic
Website: http://panasonic.net/
Location: Japan
Description:
Panasonic Corporation has developed a direct methanol fuel cell system which can produce an average power output of 20 W by increasing the output per cubic centimeter twice that of its previous prototype. Using this technology, Panasonic aims to develop a 100 W-class portable generator and start field testing in fiscal 2012 ending in March 2012.

Earlier Panasonic developed compact fuel cell stacks by reviewing the structure of its connecting parts. It also developed compact and energy-efficient balance of plant (BOP) systems including a fuel supply pump that can directly mix and adjust the concentration of methanol internally. By improving the stack technology, Panasonic has successfully doubled the average power output to 20 W while retaining the same volume with the preceding prototype. The high output methanol fuel cell allows for powering feature-laden laptop computers, which have relatively high power consumption.

3.15 Manufacturer: Nippon Oil
Website: http://www.noe.jx-group.co.jp/english/
http://www.mitsubishi.com/mpac/e/monitor/back/0710/story.html
Location: Japan
Description:
Nippon Oil is focusing on the market of fuel cells for residential with three different approaches. They are currently working with a PEM 1 kWe kerosene powered called ENEOS ECOBOY in collaboration with Ebara Ballard PEM system 10 kWe always fed kerosene in collaboration with Mitsubishi Heavy Industries, and finally to a PEM 1 kWe called ENEOS ECO LP-1 and fuelled by LPG in collaboration with Sanyo.

Currently the fuel cell system has been installed at Tokyo Disneyland. By installing the Eneos Eco LP-1, Nippon Oil aims at razing public awareness, and to promote their use by a wide range of customers. The electricity and hot water produced by the fuel cell system, which is powered by liquefied petroleum gas (LPG), will be used to provide first aid to visitors who have become ill or injured while in the park. The company also began to accept applications from ordinary households for the installation of Eneos Eco LP-1 and Eneos Ecoboy, a kerosene-fuelled home fuel cell system.

The key point is its high energy efficiency - 81%, which is far higher than the approximately 40% figure for conventional electricity generation. Of this, 35% is due to efficiency in the electricity generation, and 46% is heat recovery efficiency. ENEOS ECOBOY produces hydrogen from kerosene and generates electricity and heat through an electrochemical reaction with hydrogen and oxygen. As fuel cells generate electricity at home, there is no energy loss due to transmission. The heat generated during power generation can be used for water and space heating. In addition, as it produces electricity through an electrochemical reaction of hydrogen and oxygen, there are very few emissions of nitrogen oxides (NOX) and sulphur oxides (SOX). Its CO_2 emissions per unit of energy supplied are also 30–40% lower compared with conventional thermal power generation in power plants.

3.16 Manufacturer: Nuvera
Website: http://www.nuvera.com/
Location: US and Italy
Description:
Avanti™ is Nuvera's combined heat and power (CHP) product. It generates approximately 5 kW of electricity and 7 kW of heat. Think of this fuel cell power system as a new type of boiler that provides hot water but also offsets electricity expenses. In most applications Avanti will provide a consistent or "base load" output of thermal and electrical energy. The electric grid and conventional heating equipment are then used to support peak load demand.

Avanti integrates two key components of a fuel cell system - the fuel processor and a PEM fuel cell stack - into a single product, which allows this power system to use natural gas or propane as the primary fuel source and generate clean, efficient energy. Because we have extensive knowledge of each major subsystem, our staff developed an optimized distributed control system. This control system, which is based on the automotive-standard CAN bus architecture, is modular and flexible so it can be used in future products that require more sophisticated control algorithms and techniques. All of these components were extensively tested in real-world applications in installations around the world.

Today, Nuvera has successfully developed its third-generation Avanti system, which offers significantly higher efficiencies, improved reliability, and lower costs than previous generations. The CHP system is appropriately sized for small commercial customers who have a steady, consistent demand for thermal and electrical energy. Target applications Nuvera is currently pursuing include hospitals, hotels, dormitories, restaurants, and swimming pools.

Manufacturer:		Nuvera
MODEL:		Avanti
INPUT:		
Fuel type(s)	-	Natural gas, biogas
Flow rate	Nm3/h	
Water IN flowrate	kg/h	
Water temperature IN	℃	
OUTPUT:		
Electric power	kWe	2.3 or 4.6
Thermal power	kWt	6.9
Water OUT flowrate	kg/h	
Water temperature OUT	℃	
FEATURES:		
Type of engine	-	
Type of power output	-	
Electrical efficiency	%	
Global efficiency:	%	75
DIMENSIONS:		
Length	mm	560
Width	mm	1200
Height	mm	1400
Weight	kg	400

3.17 Manufacturer: Plug Power
Website: http://www.plugpower.com/Home.aspx
Location: US
Description:
Plug Power was founded by a joint venture between DTE Energy and Mechanical Technologies Inc. It also has a partnership with Celanese, Engelhard, General Electric, Honda R&D and Vaillant. Plug Power manufactures two stationary systems, one of which (GenSys) is a CHP which produces 5 kWe of electrical power and thermal power, 9 kWt.

Manufacturer:		Plug Power
MODEL:		GenSys
INPUT:		
Fuel type(s)	-	Natural gas
Flow rate	Nm3/h	
Water IN flowrate	kg/h	
Water temperature IN	°C	
OUTPUT:		
Electric power	kWe	5
Thermal power	kWt	9
Water OUT flowrate	kg/h	
Water temperature OUT	°C	
FEATURES:		
Type of engine	-	
Type of power output	-	
Electrical efficiency	%	
Global efficiency:	%	
DIMENSIONS:		
Length	mm	
Width	mm	
Height	mm	
Weight	kg	

3.18 Manufacturer: Sulzer Hexis
Website: http://www.hexis.com/
Location: Switzerland
Description:
Sulzer Hexis is today the largest installer of solid oxide fuel cells in the world. The company has conducted a large demonstration project based on its system by 1 HXS 1000 PREMIERE, a CHP unit kWe stationary designed for residential applications. The units are equipped with additional boilers capable of meeting the needs of a single-family house. Sulzer Hexis is currently developing Galileo 1000 N, a new series of systems with the same performances of HXS 1000 PREMIERE but a simpler design in order to facilitate the combination of different systems in multiple units.

Manufacturer:		Sulzer Hexis
MODEL:		Galileo 1000 N
INPUT:		
Fuel type(s)	-	Natural gas
Flow rate	Nm3/h	
Water IN flowrate	kg/h	
Water temperature IN	°C	
OUTPUT:		
Electric power	kWe	1
Thermal power	kWt	2.5
Water OUT flowrate	kg/h	
Water temperature OUT	°C	
FEATURES:		
Type of engine	-	
Type of power output	-	
Electrical efficiency	%	25-30
Global efficiency:	%	90
DIMENSIONS:		
Length	mm	550
Width	mm	550
Height	mm	1600
Weight	kg	170

3.18 Manufacturer: Tokyo Gas
Website: http://www.tokyo-gas.co.jp/pefc_e/index.html
Location: Japan
Description:

At Tokyo Gas the collaboration development with the Ebara Ballard Corp. group and with Matsushita Electric Industrial Co., Ltd. is under way for improvement of the system performance. The areas of effort at Tokyo Gas are to mainly develop the fuel treatment technologies to take hydrogen out of city gas, to develop heat and electric utilization technologies in order to use generated electricity and collected exhaust heat in an effective manner, and to perform the field test at houses where residents live in.

The system developed in collaboration with the latter is known as LIFUEL™, with the following specifications: 37% electric efficiency, 50% thermal efficiency, for a total efficiency of 87%. The unit can hold 200 l of hot water and gas powered.

Manufacturer:		Tokyo Gas
MODEL:		LIFUEL™
INPUT:		
Fuel type(s)	-	
Flow rate	Nm3/h	
Water IN flowrate	kg/h	
Water temperature IN	℃	
OUTPUT:		
Electric power	kWe	
Thermal power	kWt	
Water OUT flowrate	kg/h	
Water temperature OUT	℃	
FEATURES:		
Type of engine	-	
Type of power output	-	
Electrical efficiency	%	37
Global efficiency:	%	87
DIMENSIONS:		
Length	mm	
Width	mm	
Height	mm	
Weight	kg	

3.19 Manufacturer: Toshiba Fuel Cell Power Systems Corporation
Website: http://www.toshiba.co.jp/csr/en/highlight/2005/fuelcell.htm
Location: Japan
Description:

The residential FC being developed by Toshiba has a relatively small generating capacity of 700W compared with potential rival products. Toshiba selected this level of output because survey data indicated that it was the most indicated for residential power consumption during the day.

Although efficiency tends to be lower in equipment if the scale is smaller, Toshiba improved FC efficiency to fro 28% to 38%. A major element in this improvement in efficiency is the application of technology to keep the enough water in the cell by using an internal humidification process. The polymer membrane used as the electrolyte in the FC must be kept moist, but using energy to import moisture into the cell reduces the overall efficiency. Toshiba's technology recycles water and heat generated by the reaction within the cell to keep the membrane moist.

Manufacturer:		Tokyo Gas
MODEL:		LIFUEL™
INPUT:		
Fuel type(s)	-	
Flow rate	Nm3/h	
Water IN flowrate	kg/h	
Water temperature IN	℃	
OUTPUT:		
Electric power	kWe	0.7
Thermal power	kWt	
Water OUT flowrate	kg/h	
Water temperature OUT	℃	
FEATURES:		
Type of engine	-	
Type of power output	-	
Electrical efficiency	%	35
Global efficiency:	%	
DIMENSIONS:		
Length	mm	890
Width	mm	330
Height	mm	870
Weight	kg	110

3.20 Manufacturer: Toyota Motor Corporation
Website: http://www.toyota-global.com/
Location: Japan
Description:

Toyota Motor Corporation (TMC) and Aisin Seiki Co., Ltd. (Aisin) plan to provide 60 2010-model residential, solid-oxide fuel-cell (SOFC) cogeneration systems jointly developed by Osaka Gas Co., Ltd. (Osaka Gas), Kyocera Corporation (Kyocera), TMC and Aisin to the New Energy and Industrial Technology Development Organization's (NEDO) Solid Oxide Fuel Cell Verification Project. Five companies are participating in the project: Hokkaido Gas Co. Ltd., Tokyo Gas Co., Ltd., Toho Gas, Ltd., Osaka Gas Co., Ltd. and Saibu Gas Co., Ltd.

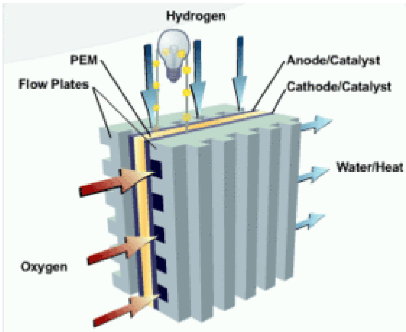
TMC and Aisin provided equipment for the project's 2009 test program. The models have overcome the technological development issues identified through earlier test programs to achieve greater energy savings and CO_2 reductions. They feature higher load efficiency of the power-generating unit during low output (partial load efficiency) and greater hot water tank capacity, resulting in more effective use of waste heat. In addition, durability and ease-of-maintenance have also been improved to enhance product marketability.

3.21 Manufacturer: Vaillant
Website: www.vaillant.de
Location: Germany
Description:
Vaillant is active in the field of fuel cells since 1999. Vaillant has already tested several CHP unit and is now working on a new system (FCU 4600) with greater efficiency and simplified technology to reduce cost. This system is still under development and therefore not yet available on the market.

Manufacturer:		Vaillant
MODEL:		FCU 4600
INPUT:		
Fuel type(s)	-	Natural gas
Flow rate	Nm3/h	
Water IN flowrate	kg/h	
Water temperature IN	°C	
OUTPUT:		
Electric power	kWe	1- 4.6
Thermal power	kWt	1.5 – 7
Water OUT flowrate	kg/h	
Water temperature OUT	°C	
FEATURES:		
Type of engine	-	
Type of power output	-	
Electrical efficiency	%	35
Global efficiency:	%	80
DIMENSIONS:		
Length	mm	890
Width	mm	330
Height	mm	870
Weight	kg	105

B) Water electrolysers using Proton Exchange Membrane technology
PEM-based water electrolysis offers a number of advantages for the electrolytic production of hydrogen and oxygen, such as ecological safety, high gas purity (more than 99.99% for hydrogen), the possibility of producing compressed gases (up to 200 bars and more) for direct pressurized storage without additional power inputs, etc. PEM electrolysers are considered as rather attractive devices to accelerate the transition to the hydrogen economy and develop a hydrogen infrastructure network (for example, for the development of re-filling stations for cars, using atomic electric power stations at night hours and also renewable power sources).

Proton exchange Membrane (PEM) fuel cells, also known as Polymer exchange membrane fuel cells typically operate on pure (99.999%) hydrogen fuel. The PEM fuel cell combines the hydrogen fuel with the oxygen from the atmosphere to produce Water, heat (up to 90℃) and electricity.



1.0 Manufacturer: h-tec
Website: http://www.h-tec-electrolyser.com/web/industrial/english/index.asp
Location: Germany
Description:
H-tec EL30 Electrolysers are ready-to-connect complete systems consisting of an electrolyser unit, a water treatment unit and a voltage transformer for connection to the grid. The core is a 30 bar PEM-Electrolyser Stack which - together with a special cooling system, a water recirculation array, the system controller management and an optional drying component - forms the electrolyser unit. Geared to the customers' requirements, our electrolysers are available with a maximum hydrogen production of between 0.3 m3/h and 3.6 m³/h. Each electrolyser configuration can be operated from 0 to 100 % of its power.

Manufacturer:		h-tec					
MODEL:		EL30/13	EL30/23	EL30/46	EL30/72	EL30/108	EL30/144
Specifications:							
PEM-Electrolyser Stack	Number of cells	13	23	46	72	108	144
H2 production, max. (wet, dew point < +4℃	m^3/h	0.33	0.58	1.2	1.8	2.7	3.6
H2 pressure	MPa	3.0	3.0	3.0	3.0	3.0	3.0
Rated power beginning	kW	1.8	3.0	5.9	9.1	14	18
Power supply	VAC VDC	35-250 41-320	55-250 65-320	100-440 120-560	155-440 185-560	225-440 270-560	300-440 360-560
Ambient temperature	℃	4 to 50					
Water preparation	Included for all						
OPTIONS							
H2 drying, He production, max (dry, dew point < -60℃)	M^3/h	0.29	0.52	1.0	1.6	2.4	3.3
DIMENSIONS:							
Length	mm	600			800		
Width	mm	560					
Height	mm	1200					
Weight	kg	120	125	130	160	170	180

1.1 Manufacturer: Proton Energy Systems
Website: http://www.protononsite.com/?x=1
Location: US
Description:
HOGEN H Series Hydrogen Generation System

The HOGEN® H Series hydrogen generation system is a fully integrated, packaged electrolysis system that produces medium pressure high purity hydrogen from water and electricity. The system includes up to three electrolyser cell stacks, as well as the support and safety systems necessary for regulating electrolyzing operations. The unit contains all of the required sensors and controls to aid in monitoring the safety, performance and automatic operation of the system. The unit is designed to operate in a well-ventilated, non-hazardous (non-classified) indoor or outdoor application.

HOGEN® H Series hydrogen generation systems produce up to 6 Nm3/hr (228 scf/hr) of ultra-high purity hydrogen gas for applications such as Material Processing, Power Plant cooling and Electronic Applications. HOGEN® H hydrogen generation systems are modular, field-upgradeable and designed to compete with delivered hydrogen anywhere in the world. A single HOGEN® H 6 Nm3/hr unit will supply the equivalent of one and one-half jumbo tube trailers every month. Multiple HOGEN® H systems may be combined for additional capacity at no extra integration cost.

Manufacturer:		Proton Energy Systems		
MODEL:		H2m	H4m	H6m
Specifications:				
PEM-Electrolyser Stack	Number of cells	13	23	46
H2 production, max. (wet, dew point < +4℃	Nm^3/h	2	4	6
H2 pressure	MPa	3.0	3.0	3.0
Rated power beginning	kW	1.8	3.0	5.9
Power supply	VAC VDC	35-250 41-320	55-250 65-320	100-440 120-560
Ambient temperature	℃			
Water preparation	Included for all			
OPTIONS:				
H2 drying, He production, max (dry, dew point < -60℃)	M^3/h	0.29	0.52	1.0
DIMENSIONS:				
Length	mm	600		
Width	mm	560		
Height	mm	1200		
Weight	kg	120	125	130

1.2 Manufacturer: Idroenergy
Website: http://www.idroenergy.it/index.html
Location: Italy
Description:
Idroenergy designs, realizes and installs plants and systems for the Hydrogen and Nitrogen on-site production of ultra-high purity gas.
Industrial research and engineering guarantee to the customer a perfect correspondence between offer and application.
The Idroenergy organization realizes turn key plants through all the steps of design, purchasing, production, installation, test, start-up, operators training and after-sale service.
The high technical specialisation allows offering personalised plant solutions, aimed to the application and the productive structure of the customer.
They follow directly installation, test and start-up of the plants in order to obtain the maximum correspondence between the plant and the customer application.
The Idroenergy company has developed different models of hydrogen generators, ranging from small to large generators.

Manufacturer:		Idroenergy	
MODEL:		8.0 Generator	19 Generator
Specifications:			
PEM-Electrolyser Stack	Number of cells		
Max H2 production	m^3/h	5,300	12,670
H2 pressure	bar	4.0	4 or 8
Rated power beginning	kWh	28	67
Power supply	V-Hz	Three phase 400-50	Three phase 400-50
Ambient temperature	°C		
Water preparation	Included for all		
OPTIONS:			
H2 drying, He production, max (dry, dew point < -60°C)	M^3/h		
DIMENSIONS:			
Length	mm	125	220
Width	mm	95	120
Height	mm	130	210
Weight	kg	620	1450

1.3 Manufacturer: H2 Nitidor s.r.l
Website: http://www.h2nitidor.com/
Location: Italy
Description:
Committed with excellence and innovation since its creation, H2 Nitidor offers hydrogen alkaline electrolysers based on VOLTANA technology. These are compact units of efficient hydrogen and oxygen gas production under pressure, up to 30 bar in absence of mechanical compression, therefore with the maximum energy efficiency.

Hydrogen can be used for a wide range of industrial applications (as float glass plants, steel production, semiconductors, photovoltaic cells, generator cooling, fats and oils hydrogenation, etc).

Special constructions may be provided on request for integration into energy handling systems based, for instance, on renewable energy, as PV or wind power. The products range from 0.25; 1.0; 10; 20; and 100.

Manufacturer:		H2 Nitidor s.r.l		
MODEL:		0,25 H2 Nitidor	20 H2 Nitidor	100 H2 Nitidor
Specifications:				
PEM-Electrolyser Stack	Number of cells			
Max H2 production	m^3/h	0,25	20	100
H2 pressure	bar	30	20	20
Rated power beginning	kWh	1	100	500
Power supply	V-Hz			
Ambient temperature	℃		5-35	5-35
Water preparation	Included for all			
OPTIONS:				
H2 drying, He production, max (dry, dew point < -60℃)	M^3/h			
DIMENSIONS:				
Length	mm	800	1600	3000
Width	mm	1000	2000	6000
Height	mm	800	2250	2250
Weight	kg			

1.4 Manufacturer: Piel Tecnologia, Ecologia
Website: http://www.digital.sm/piel-ilt/eng/index.htm
Location: Italy
Description:
PIEL was born from the ultra decennial know how of ILT Tecnologie s.r.l. about technical gas production and sale. From the headquarter in Pontedera, Pisa - Tuscany, this division produces Hydrogen and Oxygen Generators with gas delivery in a separately way and realize offers and personalized consultings in order to solve any kind of plant requirement. PIEL guarantees a total and quickly assistance to his customers due has specialized technicians and assistance points on national and international territory. The generator models comprise: P1.5; P2.4; M3.6; M5.1; M6.6; G10.2; G12; and QUINDICIMILA.

Manufacturer:		Piel Tecnologia, Ecologia		
MODEL:		P 1.5	M6.6	QUINDICI MILA
Specifications:				
PEM-Electrolyser Stack	Number of cells			
Max H2 production	l/h	1000	4400	10.000
H2 pressure	bar			
Rated power beginning	kWh			
Power supply	V-Hz	380/50	380/50	380/50
Ambient temperature	°C			
Water preparation	Included for all			
OPTIONS:				
H2 drying, He production, max (dry, dew point < -60°C)	M^3/h			
DIMENSIONS:				
Length	mm	94	94	125
Width	mm	54	69	130
Height	mm	150	160	173
Weight	kg	265	380	1140

1.5 Manufacturer: Erreduegas
Website: http://www.erreduegas.it/
Location: Italy
Description:
ERREDUE spa is a Company operating in projection, construction and sale of on site gas generators, with relevant accessories for special applications. ERREDUE spa can supply: hydrogen and oxygen generators, using electrolytic dissociation process of water molecules oxygen generators and nitrogen generators using PSA process (compressed air filtration).
The ErreDue generator produces hydrogen and oxygen gases perfectly separated one by the other, through electrolytic dissociation process of water molecules; for this process the generator needs for its functionality, demineralised water and electrical power supply connection.
To be immediately useful, for many applications, the gas is directly produced at the needed operating pressure and with the appropriate quality characteristics. In the applications which need an higher title value, can be provided with an additional purification device or, for bigger generators, the additional purification device can be included into the generator itself.
The ErreDue guaranteed quality, the safe and ecological characteristics of the produced gases, and the low price operating costs, together with other important characteristics, make it a front liner on the technology currently available on the market.

Manufacturer:		Erreduegas
MODEL:		
Specifications:		
PEM-Electrolyser Stack	Number of cells	
Max H2 production	Nm^3/h	
H2 pressure	bar	
Rated power beginning	kWh	
Power supply	V-Hz	
Ambient temperature	℃	
Water preparation	Included for all	
OPTIONS:		
H2 drying, He production, max (dry, dew point < -60℃)	M^3/h	
DIMENSIONS:		
Length	mm	
Width	mm	
Height	mm	
Weight	kg	

C) Hydrogen storage systems

1.0 Manufacturer: ITM POWER
Website: http://www.itm-power.com/page/15/Hydrogen+Storage.html
Location: UK
Description:
ITM has developed systems design and integration expertise covering the compression, storage and dispensing of high pressure gaseous hydrogen up to 350 bar.
ITM is also very active in the certification, codes/standards and legislation concerning hydrogen storage; installation of systems within domestic and industrial settings will be crucial to any future hydrogen economy and ITM is positioning itself to be able to understand and influence future legislation.
ITM Power's Transportable Hydrogen Refuelling Station (HFuel) is a self-contained module suitable for refuelling hydrogen-powered road vehicles and forklift trucks.
It is well suited to small fleet and early 'hydrogen highway' applications of both fuel cell and hydrogen engine vehicles (FCV and HICEV).
It is based around a modular platform (standard freight containers) and can be expanded at any point after the initial installation enabling a staged roll-out of hydrogen fuel.
HFuel generates hydrogen by electrolysis, compresses it, stores it and dispenses the gas on demand at high pressure (nominally 350 bar/35MPa).
It requires an on-site water and electricity supply but is otherwise an autonomous solution for refuelling hydrogen-powered vehicles.
Zero-Carbon Fuel
Because HFuel is based on an electrolyser it is uniquely able to produce zero-carbon hydrogen if linked to a renewable power source or a supply of 'green' electricity. The fuel delivered to the vehicle is then carbon-free and no atmospheric carbon emissions result from its use.
HFuel provides a pathway for eradicating emissions associated with light duty commercial vehicles and materials handling in warehouses and factories.
Unlike battery recharging stations HFuel enables the user to quickly recharge a vehicle to 100% capacity. This enables hydrogen to be used to decarbonise return-to-depot and shift work vehicles that have a higher daily mileage requirement.

Manufacturer:		ITM POWER
MODEL:		HFuel
INPUT:		
Fuel type(s)	-	
Flow rate	Nm3/h	
Water IN flowrate	kg/h	
Water temperature IN	°C	
OUTPUT:		
Electric power	kWe	
Thermal power	kWt	
Water OUT flowrate	kg/h	
Water temperature OUT	°C	
FEATURES:		
Type of engine	-	
Type of power output	-	
Electrical efficiency	%	
Global efficiency:	%	
DIMENSIONS:		
Length	mm	
Width	mm	
Height	mm	
Weight	kg	


ITM POWER

Annex C ATES and BTES

Aquifer Thermal Energy Storage

Principle of Operation

An aquifer thermal energy storage system (ATES) is a storage system for low enthalpy thermal energy in natural water-bearing underground layers (the aquifer). The transfer of thermal energy to the aquifer is realized by extracting and re-injecting ground water from one or more wells and as such, this system is considered an “open” system. In summer, the relatively cold groundwater (8-12℃) is extracted for the cooling of buildings. This involves heating the groundwater, typically to values between 15 and 20℃ and subsequently re-injecting it into the aquifer. During the heating season, the warm groundwater is either used in combination with a heat pump to provide heating for buildings or a cooler is used to cool the groundwater again.

ATES Types

Doublet configuration
The basis of the most common ATES configuration consists of a pair of wells: a cold and a warm well. To increase the maximum output power and storage size, similar configurations with multiple wells (multiple pairs or multiple injection wells) can be implemented. The distance between each injection and extraction well is usually between 50 and 250m to prevent a thermal breakthrough between the wells (mixing of cold and warm water). This ATES configuration is schematically presented in Fig. 1. In general, the geometry of the wells strongly depends on local conditions, such as the geology and the energy demand profile.

In summer, when cooling is desired, cold ground water (av. 8-12℃) is extracted from one well (cold well) and the cold is directly extracted from the ground water to the building circuit using a heat exchanger, Fig. 1a. The heated water is subsequently injected into the second well (warm well). In winter, this process is reversed (cyclic/bidirectional system) and heat is transferred to the building circuit, either with a heat pump or directly using the same heat exchanger and the cooled water is re-injected into the cold well. Consequently, in summer heat is stored for use during the winter, while in winter cold is stored for use during the summer and hence, one also refers to ATES as a seasonal storage system.

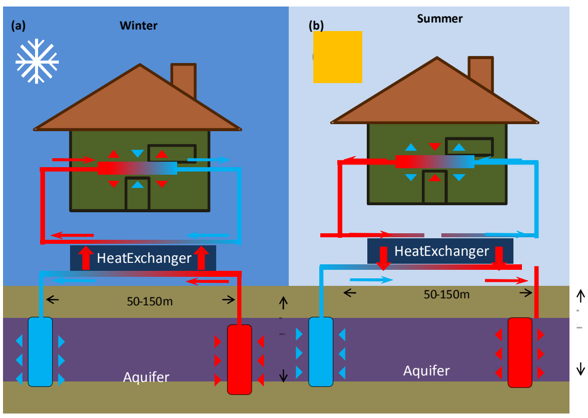


Fig. 1: Doublet ATES system operation principle during (a) winter and (b) summer.

Mono source configuration
For smaller projects, a mono source design can be an equivalent alternative for the doublet structure. Here, only one source is drilled for the extraction and injection. The required physical separation between the warm and cold well is realized by a vertical separation rather than lateral. Evidently, this design requires an aquifer with a sufficient thickness. Ideally, a less permeable layer is located in between the

wells. The principle of this configuration is shown in Fig. 2. Due to the lower investment cost as compared to the doublet set-up, this design is especially suited for smaller installations with limited power outputs.

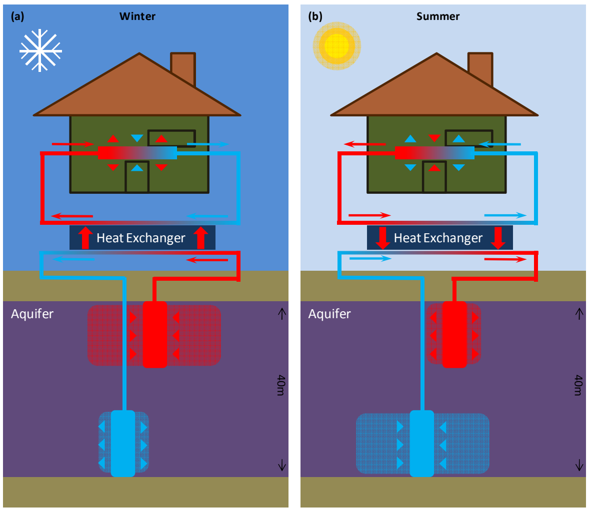


Fig. 2: Mono source ATES system during (a) winter and (b) summer.

Recirculation system

Recirculation is similar to the above mentioned ATES configurations except for the direction of the groundwater flow which is the same all year round (continuous/unidirectional system). As such, there is only one extraction/injection well (this can be realized in a doublet or mono source configuration). The principle of operation is schematically presented in Fig. 3 for a doublet configuration. In summer, the cold groundwater is extracted to provide natural cooling and the warm water is subsequently reinjected into the injection well. To prevent thermal pollution of the underground (and the concomitant decrease in system performance) the groundwater is cooled below the natural groundwater temperature during the winter and injected into the well. This cooling can be achieved with a conventional cooling technique, such as cooling tower, heat pump, air handling unit, etc. The system should be dimensioned in such a way that over time no net heating or cooling of the underground occurs. The advantage of this system is that cooling can be provided all year round and that the implementation is simpler and cheaper as compared to a cyclic system. This type is commonly used in industry since cooling is required all year long.

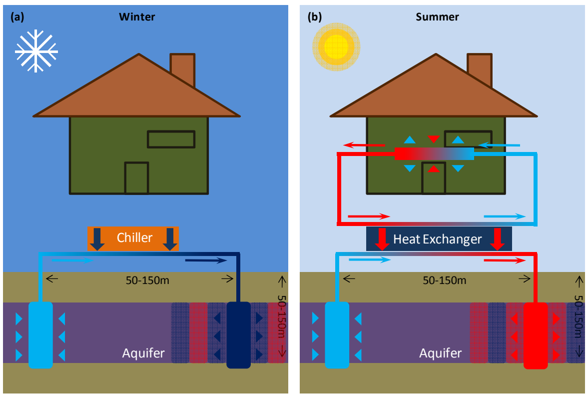


Fig. 3: Operation principle of a recirculation ATES system during (a) winter and (b) summer.

Boundary Conditions

The performance of an ATES system strongly depends on various parameters and conditions:

- Hydrogeological characteristics of the underground
- Type of installed HVAC equipment, power and energy demand
- Balance between heat and cold extraction
- Climate conditions

Hydrogeological Properties
The presence of an aquifer at a suitable depth is crucial for the implementation of an ATES system. This condition represents also one of the major limitations of ATES, since, for instance in Flanders, Belgium only one third of the total area might have a suitable aquifer. However, not only the presence but also the depth of the aquifer plays an important role. Usually, the depth of the well varies between 50 and 150m. Aquifers located at a depth of more than 150m are generally not economically feasible for thermal energy storage. In the case of a single source system, the thickness of the aquifer must be at least 40m to avoid a thermal breakthrough.[referentie boek Wim] In Flanders and The Netherlands, ground water flows of 10 to 200m³/h/doublet are achievable. To evaluate the characteristics and performance of an aquifer, several parameters are important:

- The thickness of the aquifer, usually between 20 and 40m. Thick aquifers ensure a large storage volume and are in general less prone to thermal pollution (see below).
- The permeability of the aquifer has a large influence on the flows, and thus the power, that can be extracted from the wells. The transmissivity (permeability × the aquifer thickness) should be higher than 15 Dm.[5]
- The natural groundwater flow should be as low as possible to minimize the thermal losses (<10-30m/yr).[6]
- The thermal properties of the ground layers confining the aquifer have a large effect on the thermal losses of the aquifer. Well insulating layers are preferred.

HVAC Equipment
Classic low-temperature cooling equipment is designed for operating in the 6/12℃ ice-water regime. However, to obtain such temperatures in an ATES set-up, the injection of ~2℃ groundwater is required during winter time. However, the amount of days that such cold groundwater can be produced with outdoor air in moderate climates is mostly insufficient. Therefore, the wells are generally operated in a higher temperature regime (10/18℃). Consequently, the HVAC equipment in the building should be designed or adjusted for high-temperature natural cooling. On the other hand, the temperature can also be further reduced using a reversed heat pump (active cooling).

Similarly, in winter, a low-temperature heating system is required when operating an ATES since the supply temperatures are in general considerably lower compared to classic heating systems. Even when employing a heat pump, the temperature regime is limited to 40/45℃. Especially in renovation projects, these temperature regimes might result in problems.

The temperature evolution of the ATES set-up plays an important role as well and strongly depends on the type of HVAC equipment installed. For instance, to deliver 100 kW heat power with a temperature difference of 5℃ ($T_{supply} - T_{return}$) requires approximately 17 m³/h groundwater, while with a decay of 10℃, only about 9 m³/h is required. This has definitely a positive effect on the energy performance.

The overall performance of the system also depends on the duration of the heating/cooling demand. A system designed to deliver peak cooling during summer will be less efficient than a system dimensioned on the base load. For a correct dimensioning of the ATES system, it is indispensable to calculate the overall cooling and heating demand, since over-dimensioned systems with, for instance, multiple smaller wells, tend to have poor performances.

Balance between the Heat and Cold Demand
For the application of ATES, it is important to create a good balance between the heat and cold extraction. When a structural imbalance exists, the temperature of the underground might change significantly over time which has a negative impact on the overall performance of the system. Additional equipment might

be necessary to eliminate this imbalance by additional heating or cooling of the underground. A good balance is often also required to receive a permit for the installation.

A structural imbalance might also occur if power is extracted from the aquifer by nearby systems (ground water wells, other ATES systems, …). Since the thermal energy is stored in a large volume, extending beyond the building dimensions, it is important to identify other extracting systems in the neighbourhood.

Climate Conditions
The application of underground storage systems is strongly coupled to the climate as well. One of the main reasons is the fact that the temperature of the underground depends on the average ambient temperature in the air. Ground coupled storage systems are therefore less feasible in tropical and arid climates. Furthermore, in regions with high humidity there is a necessity for cooling which allows condensation. In such cases, direct cooling may not be sufficient. Continental climates, on the other hand, are perfectly suited for the application of ATES.[7]

Environmental Impact

The implementation of an ATES system has also a significant impact on the environment. Besides the positive effects, such as primary energy and CO_2 emission reduction, it may also pose risks for the environment. Both effects will be shortly summarized here.

Positive Effects
Although the choice for an ATES system is often an economical one, the positive effects on the environment are a major advantage as well compared to conventional techniques. The correct implementation of an ATES system leads to a significant decrease in primary energy consumption and greenhouse gas emissions. A study by DWA Installatie- en energieadvies, The Netherlands, which evaluated 13 different ATES projects (cold storage) in tertiary buildings revealed an average reduction of 60% on the electricity and 50% on the natural gas consumption as compared to a conventional reference system. This corresponds to an average CO_2 emission reduction of 60%.[8]

Potential Risks
A first potential risk is the mixing of groundwater with different qualities, for instance mixing of salt/brackish water with freshwater, or polluted with clean water. This phenomenon might occur if the extraction and injection well are located in different groundwater zones or when the wells are drilled through multiple aquifers. The operation of an ATES can also increase the spreading of pollution due to the circulation of the groundwater. Furthermore, when the wells are located in groundwater layers with different chemical composition, for instance in oxygen, nitrate, or iron rich layers, the oxidation of compounds can occur. To avoid such risks, it is important that the wells are located in the same aquifer and that the quality and composition of the injected water is similar as the extracted water.

Secondly, the leaking of glycol or other cooling liquids to the groundwater will contaminate the underground with hazardous and toxic substances. Leakage can occur in the heat exchanger where the internal building circuit and the external groundwater circuit exchange thermal energy. Keeping the groundwater circuit at overpressure and using a double sided exchanger will drastically decrease this risk. Other chemical pollution risks include the leaching from installation materials and the dissolution or precipitation of carbonates and silicates and can be avoided by proper installation and choice of materials.

Extracting groundwater has also an effect on the height of the water level and may cause (temporary) desiccation of the underground. However, the influence of this phenomenon on the environment is negligible. Injecting groundwater, on the other hand, may lead to a (temporary) increase in the water level of the aquifer and can have a significant impact on the fauna and flora in the underground. For instance, roots and underground animals might die due to lack of oxygen which is normally present in the pores. Furthermore, it may also lead to flooding in underground buildings such as tunnels, basements, parking garages etc.. The risk can be limited by placing the wells deep enough, ideally in a highly permeable aquifer with a low permeable interface layer with the surface.

Fourthly, thermal pollution of the underground after long term use of the ATES system is a potential risk. This effect predominantly occurs in poorly designed systems with a poor thermal balance between the extracted and the injected groundwater or in systems where a rather high groundwater flow exists. Since the temperature differences are rather small (8-25°C), no considerable effects are expected on the microbiological composition of the groundwater.[9] A thick and permeable aquifer significantly reduces the thermal influence on the underground.

Leakage of the wells will lead to mixing of the groundwater with the surface water. The leakage is often due to an incorrect installation or operation of the system, for instance, a bad sealing of the well or an excessive injection pressure. A well designed and build system can reduce these risks.

Finally, the drilling of the wells implies the introduction of unnatural materials, such as plastics, grouting materials, etc. into the underground. In the long term, these materials might degrade and release toxic or polluting compounds into the underground or underground water.

More detailed information on the potential risks and preventive measures can be found in references

As a result of these possible risks the implementation of ATES is governed by strong regulations and often a permit is required. These regulations are mostly defined by local governments resulting in a large scattering of regulations throughout Europe.

Economical aspects

Performance
The coefficient of performance (COP) is defined as the delivered cooling/heating divided by the electricity consumption. The COP of an ATES system is typically 20-40 for natural cooling, while a conventional chiller has a COP of 2.5-3.5 in the 6/12℃ regime. In combination with a heat pump, these installations reach a COP of 4-6 for heating. Overall, these systems are one of the most energy efficient systems for heating and cooling.

The investment cost strongly depends on the power of the system, i.e. the extracted ground water flow. An ATES system costs between 500 €/kW for larger systems and 800 €/kW for smaller systems. This amount covers the whole installation of the system including drillings, filters, heat exchanger, pipes, etc.. The heat pump (175-250€/kW_{th}), however, is not included. The ATES system has a life expectancy of about 20-30 years and maintenance cost are estimated to be 2% of the total investment. An evaluation of tertiary buildings in The Netherlands revealed that the return of investment time is generally below 6 years. Evidently, the economical feasibility of ATES systems largely depends on current energy prices and governmental subsidies.

Examples

	Industry, Westerlo, Belgium (recirculation)[21]	Hospital, Herentals, Belgium[22]	Hospital, Sint Truiden, Belgium[23]
ATES specifications			
Heat pump power	n.a.	200 kW_{th}	700 kW_{th}
ATES power	3000 kW_{th}	700 kW_{th}	900 kW_{th}
Heat demand coverage	n.a.	35 %	57 %
Cold demand coverage	100%	100%	100 %
Wells	3 doublets	1 doublet	2 doublets
Depth	65 m	70 m	/
Aquifer thickness	> 50 m	80-90 m	/
Well separation	200 m	/	/
Extracted groundwater	541,665 m³/yr	80,000 m³/yr	105,000 m³/yr
Groundwater flow	200 m³/h	100 m³/h	100 m³/h
Extraction temperature	12 ℃	10 ℃	10 ℃
Max. injection temperature	25 ℃	25 ℃	18 ℃
Economical aspects[1]			
Heat pump	n.a.	115,000 €	112,000 €
ATES system	1,314,000 €	450,000 €	857,000 €
Annual savings	29,408 €	20,000 €	38,500 €
SPF cooling	/	23	23
SPF heating	/	4.6	4.6
Return of investment time	2.5	6.2	8.3
Environmental aspects[2]			
CO_2 savings	331 ton/yr (74%)	135 ton/yr (48%)	216 ton/yr (35%)

[1] V.A.T. excluded.
[2] Based on a comparison with a *business as usual* system.

Borehole Thermal Energy Storage

Principle of Operation

Borehole thermal energy storage (BTES) is a method for storing thermal energy in the underground. The thermal energy is supplied to and extracted from the underground by means of vertical heat exchangers mounted in boreholes. These heat exchangers are connected to a closed hydraulic circuit carrying the transfer fluid. By integrating multiple boreholes and heat exchangers a large storage capacity can be created for either low enthalpy thermal energy (heat and cold) or for high temperature heat (<100℃).

Low Enthalpy BTES

A common BTES system consists of plastic loops serving as heat exchangers, inserted into a grid of boreholes, generally 20 to 150m deep and 2 to 10m apart. The number and depth of boreholes will determine the storage volume and thus the maximum power of the system. A schematic layout of a BTES system is shown in Fig. 4. The loops are connected to a closed hydraulic circuit carrying water to transfer the heat to the underground. Generally, glycol is added to the water as an antifreeze.

In winter, the water/glycol mixture is presented to a water-air/water heat pump for the heating of the building. The transfer fluid which is cooled down by this process, is subsequently pumped through the vertical ground heat exchangers to extract heat from the underground and to heat up the fluid. At the end of the heating season, underground temperatures are commonly around 0℃. In summer, the stored cold can be utilized for cooling purposes, either via natural cooling or with a reversed heat pump. The resulting waste heat is stored in the underground for use in winter. At the end of the cooling season temperatures can easily reach 16℃. As a result, one also refers to BTES as seasonal storage.

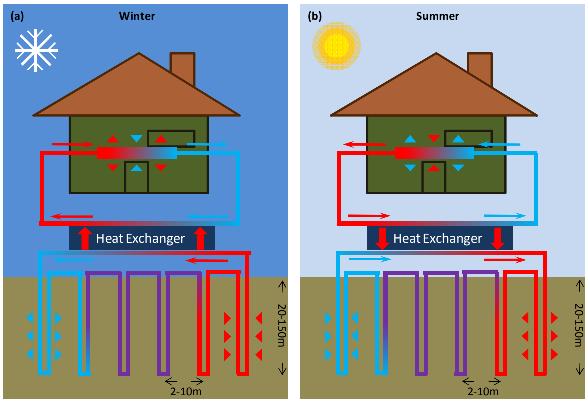


Fig. 4: Low enthalpy BTES system operation principle during (a) winter and (b) summer.

High Temperature BTES

When the overall heat demand in winter strongly exceeds the cooling demand in summer, for instance in greenhouses, or buildings in cold climates, or when high temperatures are required for existing high-temperature supply systems or sanitary hot water systems, one can consider high-temperature storage. By actively loading the underground with heat during summer, for instance by solar collectors, combined heat and power plants, waste heat, etc., the underground can be heated to high temperatures (< 90℃). This heat can be used in winter to provide high-temperature heat, even without additional heat pump.

Boundary Conditions

The performance of a BTES system strongly depends on various parameters and conditions:

- Geological characteristics of the underground
- Type of installed HVAC equipment, power and energy demand
- Balance between heat and cold extraction

- Climate conditions

Geological Properties
In general, these closed loop systems can be implemented in all types of geology. However, the applicability can be limited by the thermal properties of the underground, drilling issues and hydrogeological properties.

First of all, The thermal characteristics of the underground will play a major role in the storage capacity and power delivery of the BTES set-up. A higher thermal conductivity of the ground will result in an increased extraction rate of heat/cold from the underground and as such, in an increased storage capacity and power delivery. For instance, limestone has a significantly larger conductivity as compared to clay. Furthermore, water saturated layers also exhibit a higher thermal conductivity compared to dry layers (for instance, wet shale versus dry clay). Consequently, the type of underground will have a large impact on the design of the BTES system, i.e. a large thermal conductivity may lead to a significant reduction in the required length of the heat exchanger. Concomitant with a high thermal conductivity of the underground, a high conductivity of the borehole itself is desired as well. This can be achieved by using suitable grouting and filling materials, such as betonite, quartz sand.

Secondly, the geological formation and underground hardness will determine the required drilling technology which in turn has a large impact on the total cost of the implementation of a BTES system.

Thirdly, closed loop systems may also be affected by groundwater flows. As already mentioned, water has a beneficial impact on the thermal conductivity, however undesired groundwater flows may also lead to storage losses. Furthermore, detailed hydrogeological information is necessary to avoid mixing and leaking due to drilling through multiple water layers and drilling in Artesian layers.

HVAC Equipment
Since the ground temperatures vary between 0 and 16℃, a cooling system designed for operation in a high temperature regime (14/18℃) is required to ex ploit the full cooling potential of the BTES. Similarly, for heating with a low enthalpy BTES - heat pump combination, a low-temperature heat supply system able to deliver sufficient power to the building needs to be implemented.

Balance between Heat and Cold Demand
Similar to ATES, it is important for the application of BTES to create a good balance between the heat extraction and injection. When a structural imbalance exists, the temperature of the underground might change significantly over time. This effect has a negative impact on the overall performance of the system. Additional equipment might be necessary to eliminate this imbalance.

Climate Conditions
The climate conditions discussed above for ATES systems, also apply to BTES systems. Therefore, BTES is also less feasible in tropical and arid climates, whereas continental climates are ideal candidates for BTES systems.

Environmental Impact

The implementation of an BTES system has also a significant impact on the environment. Besides the positive effects, such as primary energy and CO_2 emission reduction, it may also pose risks for the environment.

Positive Effects
Much like ATES, a BTES system also has, besides economical advantages, positive effects on the environment as compared to conventional techniques. A good implementation of a BTES system leads to a significant decrease in primary energy consumption and greenhouse gas emissions. Studies by the Flemish Institute for Technological Research shows that BTES systems used for heating and cooling of buildings may reduce the CO_2 emissions up to 30%.

Potential Risks

Since BTES systems are closed systems, many of the potential risks related to groundwater as described in the ATES section, do not apply. However, in some cases the boreholes penetrate water layers and appropriate measures need to be implemented to prevent mixing and leaking of the groundwater, for instance sealing of the borehole at the interface of the water layer.

Other risks of the operation of a BTES system include leaks in the hydraulic system which might result in the release of the glycol mixture in the underground. Even though commonly used glycols are not considered very toxic and rapidly break down in the underground (5-10 days), their decomposition is accompanied by high levels of biochemical oxygen demand impacting micro-organisms living in the underground.

Thermal pollution is the major source of environmental concerns for BTES systems. In case of a structural imbalance between the heat and cold demand, the underground temperature may significantly change after long term use. This will not only destroy the efficiency of the system, but might also affect the chemical and biological composition of the underground. The latter effects are especially relevant for high-temperature storage. Effects such as precipitation of carbonates, deionization and acidification of the groundwater have been observed after the implementation of a BTES system.

Similar to the ATES systems the drilling of the boreholes also implies the introduction of unnatural materials, such as plastics, grouting materials, etc. into the underground. In the long term, these materials might release toxic or polluting compounds into the underground or underground water. In general, this effect can be more pronounced in BTES systems as compared to ATES since more boreholes and thus more materials are required.

Economical aspects

Performance

The coefficient of performance (COP) of a well designed BTES system is similar to ATES systems, being typically 20-40 for natural cooling. In combination with a heat pump, these installations reach a COP of 4-6 for heating. Overall, these systems are among the most energy efficient systems for heating and cooling.

Due to the relatively large amount of boreholes as compared to ATES, the drilling costs of a BTES system are considerably higher which leads to a relatively strong increase in installation costs. Based on several studies, the initial investment for a BTES system (excluding the heat pump) reach about 800-1200 €/kW. Again, the economical feasibility strongly depends on current energy prices and governmental subsidies.

Examples

	Office Building, Melle, Belgium[31]	Resting Home, Beveren, Belgium[32]	Office Building Torhout, Belgium[33]
BTES specifications			
Heat pump power	500 kW_{th}	300 kW_{th}	130 kW_{th}
BTES power	350 kW_{th}	255 kW_{th}	100 kW_{th}
Heat demand coverage	76%	52%	94 %
Cold demand coverage	83%	100%	52%
Boreholes	90 (10×9)	42 (6×7)	20 (4×5)
Depth	125 m	150 m	150 m
Borehole distance	4 m	5 m	4.5 m
BTES area	1,152 m²	750 m²	310 m²
Storage volume	144,500 m³	112,500 m³	46,500 m³
Max. fluid temperature	14/18 ℃	14/18 ℃	14/18℃
Min. fluid temperature	-1/4 ℃	0/5 ℃	0/5 ℃
Economical aspects[1]			
Heat pump	90,000 €	84,000 €	26,000 €
BTES system	375,000 €	213,000 €	117,000 €
Annual savings	27,111 €	19,148 €	7,000 €
SPF cooling	6	19.6	6
Return of investment time	7.9	8,4	9.5
Environmental aspects			
CO_2 savings[2]	128 ton/yr (31%)	67 ton/yr (26%)	33 ton/yr (32%)

[1] V.A.T. excluded.
[2] Based on a comparison with a *business as usual* system.

Comparison ATES – BTES

	ATES	BTES
Specifications[18]		
Extracted ground water flow	10-200 m³/h/pair	n.a.
Natural ground water flow	< 30 m/yr	< 10-20 m/yr
Power extraction	120-2000 kW/pair/10℃	20-60W/m
Temperature range (C)	10/18℃	14/18℃
Temperature range (H)	30/45℃	30/45-90℃
Life span	20-30 yr	50 yr
Storage power	30-40 kWh/m³	15-30 kWh/m³
Application	industrial/tertiary	industrial/tertiary
COP (cooling)	20-40	15-40
COP (heating)	4-6	4-6
Economical aspects		
Installation	450-900 €/kW	800-1200 €/kW
Maintenance[1]	2%	2 %
Return of investment time	3-8 yrs	6-10 yrs
Environmental aspects		
CO_2 savings	35-75%	20-70%

[1] Percentage of total investment.

Annex D Performance characteristics

Power Generation Characterization

Generator type	PV mono- /multi- cristalline Si	PV amorphous Si	PV CIS	PV CdTe
Auxiliary electric energy required	-	-	-	-
PV – Peak power (Wp/m^2)	135-145	55 – 65	80-100	55-80
PV – Cell efficiency (%)	15 - 16	6 – 7	9-11	6-9
Annual energy production [1] (kWh/m^2 for PV; kWh for wind turbine)				
Annual energy – climate A	130-140	50-60	80-95	50-80
Annual energy – climate B	150-160	60-70	90-110	60-90
Annual energy – climate C	200-220	80-95	120-150	80-120
Max rate of power increase/drop (%/sec) [2]	Following change in solar irradiance			
Cost of the equipment (€/kW or €/kWh for average year)	2.30 Euro/Wp (average module retail price excluding installation, nov 2011; solarbuzz.com)			
Requirements for energy-infrastructure	If more than 1 kWe is installed in all dwellings the usual power grid needs to be enlarged (NL)			

1 To be established for one or more reference climate zones.
Maybe these are already available form other EU projects

2 Natural fluctuations in solar radiator or wind speed will cause power increase or drop. The speed of change may be a challenge for the power grid and other power suppliers to maintain a stable power supply.

Generator type	Small wind turbines	Large wind turbines	Deep Geothermal
Auxiliary electric energy required	5%	10%	
Peak power (Wp/m^2)	0,20-0,40	0,40-0,80	
Efficiency (%)	< 59%	< 59%	
Output power range (kW) (nominal output power)	0,9kW-12kW	0.75 MW – 8MW	20-120 MW_e for units utilizing steam from the ground; or 1-3 MW_e in hot water dominated fields with binary cycle plants
Minimum power (% of nominal power)	0	0	x
Wind - Annual turbine efficiency (%)	13-20	30-40	x
Annual energy production [1] (kWh/m^2 for PV; kWh for wind turbine)	150-400 kWh/m2	800-1200 kWh/m2	
Annual energy – climate A	--	--	
Annual energy – climate B	--	--	
Annual energy – climate C	--	--	
Max rate of power increase/drop (%/sec) [2]	0.5	0.8-1.5	
Cost of the equipment (€/kW or €/kWh for average year)	2,4-9,1€/W	1 €/W (land) 2 €/W (sea)	600 – 2200 €/ kW*
Requirements for energy-infrastructure	None special requirements. For auto consumption, regulator of charge, and lead batteries capacity. Low voltage installation.	3-9 times rotor dimension between wind turbines Transportation of components Access to wind farm Substation capacity and distance	suitable ground

Heat Generation Characterization

Generator type	Condensing combi boiler for dwellings (HR 107)[3]	Condensing large boiler (HR 107)	Atmospheric boiler	Combi electric heat pump for dwellings
Fuel type (gas, oil, electricity, biomass)	Gas	Gas	Gas	Electricity
Heat source type (S - soil, W - ground water, A - air, …) [2]	---	---	---	S, W
Heating functions (H = heating, W = DHW)	H, W	H (W indirect)	H (Windirect)	H, W
Auxiliary electric energy				
- standby (W)	2 – 10	10 ?	10	2 – 10
- nominal operation (W)	50 – 150 W	2 - 5 W/ kW ?		150-250 W (2 pumps)
Load range (kW input power) [1]	20 - 40	40 – 1000 or more	40-300 or more	3 – 5 (excl. aux. heater)
Power range (kW output power)	19 - 38	35 – 900		12 – 20
Modulating range (min % nom load)	20 - 25	20 - 25		100 (no moduation)
Minimum on-time (sec)	120	120		300
Max. supply temperature (°C)	80 - 90	80 - 90	80-82	45-55
Min. source temperature (°C) [2]				
Annual efficiency [1] or COP [2]	89-99	89-99	85	
- Heating	95	90	85	3 - 6
- DHW	65 - 80	---	---	2,5 – 3,5
Cost of the equipment (€/kW output power)	230	220	200	400
Requirements for energy-infrastructure	Natural gas	Natural gas	Natural gas	If heat pumps are installed in all dwellings the usual power grid needs to be enlarged (NL)

1 upper calorific value
2 only for heat pumps, COP related to fuel type.
3 HR = Hoog Rendement

Generator type	Electric resistance systems [3]	Solar Thermal Solar collectors	Solar Thermal Road Collectors
Fuel type (gas, oil, electricity, biomass)	Electricity	---	---
Heat source type (S - soil, W - ground water, A - air, …) [2]	---	Solar radiation	Solar radiation
Heating functions (H = heating, W = DHW)	H, W	HW	Low temp heating , DHW, dissipation
Auxiliary electric energy	5 W		
- standby (W)	10 W	1W	10-40
- nominal operation (W)	10 W	25 W pump	200-400
Load range (kW input power) [1]	1 -3 kW e	-	10-20kW
Power range (kW output power)	1 -3 kW e	0-800 W/m2 Depends on irradiance	0,063kW/m2 @ 1000W/m2
Modulating range (min % nom load)	0-100%	0 (no irradiance)	No min limit
Minimum on-time (sec)	1 s	10 min. Depends on control and variation solar irradiance	60-120
Max. supply temperature (°C)	82-91	50-250 C, depends on collector type, system type, irradiance and heat transfer fluid	50-60
Min. source temperature (°C) [2]	---	---	---
Annual efficiency [1] or COP [2]	99%	---	---
- Heating	99%	40-20% Depends on dimensioning and climate	30%
- DHW	99%	50-25% Depends on dimensioning	
Cost of the equipment (€/kW output power)	100	200-1000	100-160
Requirements for energy-infrastructure	Electrical cables sized accordingly	there is a requirement for the building (SE/S/SW-facing, little shading, available roof)	Thermal storage infrastructure (Water tanks) Pumping system Dissipation circuit (optional). Heat exchange devices

1 upper calorific value
2 only for heat pumps, COP related to fuel type.
3 All electrical energy is converted in heat energy. Losses are in the energy transformation fuel / electrical energy.

Generator type	Air source heat pump	Geothermal heat pump
Fuel type (gas, oil, electricity, biomass)	Electricity	Electricity
Heat source type (S - soil, W - ground water, A - air, …) [2]	Air	Rock or Soil
Heating functions (H = heating, W = DHW)	H; DHW	H; DHW
Auxiliary electric energy		
- standby (W)		
- nominal operation (W)		50W per kW installed
Load range (kW input power) [1]		
Power range (kW output power)	Up to $5MW_e$	Up to $5MW_e$
Modulating range (min % nom load)		
Minimum on-time (sec)		
Max. supply temperature (°C)	28-35ºC for DHW 50-85ºC for Heating	50-55ºC
Min. source temperature (°C) [2]	-15ºC	-4ºC
Annual efficiency [1] or COP [2]	1,2-3,2	3-5
- Heating	---	---
- DHW	---	---
Cost of the equipment (€/kW output power)	200€/kW	220€/kW
Requirements for energy-infrastructure		Suitable ground

1 upper calorific value

Cogeneration Characterization

Generator type	Organic Rankine Cycle (ORC)	Internal Combustion Engines (ICE)	External Combustion Engines (Steam turbine)
Fuel type (gas, oil, biomass)	Gas-oil-biomass	Gas-oil-biomass	Gas-oil-biomass
Heating functions (heating, DHW)	H DHW	H DHW	H DHW
Auxiliary electric energy			
- standby (W)	---	15	---
- nominal operation (W)	---	50	3-4% of nominal size (4)
Load range (kW input power) [1]			
Power range (kW output power)	Few kWe / 1-2 MWe	4-100 kWe	50 kWe / 10 MWe
Modulating range (min % nom load)	50% min.	50% min.	50% min.
Minimum on-time (sec)		10 s	3600 s ?
Max. supply temperature (°C)		78-110	150 (6)
Performance, method A [2]		N.A.	N.A.
A - Annual electric generation efficiency (%) [2]	<25%	N.A.	N.A.
A - Annual heat generation efficiency (%)[2]	~80%	N.A.	N.A.
Performance, method B [3]	N.A.	N.A.	N.A.
B - Annual electric generation decrease (Δ%) [3]	N.A.	N.A.	N.A.
B. - Annual heat generation efficiency (%) [3]	N.A.	N.A.	N.A.
Cost of the equipment (€/kW)	1000/2500	500	1400
Requirements for energy-infrastructure			

1 Upper calorific value
2 Method A is used for gas engines and turbines designed for co-generation. The energy performance is characterized by more or less fixed efficiencies. The heat efficiency may be slightly higher when applied in low temperature heating systems.
3 Method B is used for (larger) gas turbine power plants. When heat is drawn off at temperatures above 70-90°C, a decrease in electric efficiency results. This decrease is depending on the level of the useful heat temperature, so more figures can be given for annual electric generation decrease as a function of supply (draw off) temperature.
4 Electrical engine is utilized to keep rotating shaft and steam turbine.
5 Stirling engine need slow start-up. It cannot easily modulate, since the hot source system (heating the internal gas) has big inertia.
6 pressurised steam (that can be condensed to hot water)

Generator type	External Combustion Engines (Stirling Engine)	Hybrid PV/Thermal
Fuel type (gas, oil, biomass)	Gas-oil-biomass	-
Heating functions (heating, DHW)	H DHW	HW
Auxiliary electric energy		
- standby (W)	50	-
- nominal operation (W)	N.A.	25 W pump
Load range (kW input power) [1]		-
Power range (kW output power)	1-10 kWe (3-55 from TPG)	Thermal 0-700 W/m2 Electrical 0-160 W/m2 Depends on design, solar radiation and storage temperature
Modulating range (min % nom load)	90% (5)	0
Minimum on-time (sec)	1200 s	10 min Depends on variation solar radiation and control
Max. supply temperature (°C)	90	40-100 C, depends on collector type, system type, irradiance and heat transfer fluid
Performance, method A [2]	N.A.	
A - Annual electric generation efficiency (%) [2]	N.A.	6-13% depends on type of PV
A - Annual heat generation efficiency (%)[2]	N.A.	40-20% Depends on application and dimensioning
Performance, method B [3]	N.A.	
B - Annual electric generation decrease (Δ%) [3]	N.A.	
B. - Annual heat generation efficiency (%) [3]	N.A.	
Cost of the equipment (€/kW)	7000	300-1100 euro/kW_th + 2200-2500 euro/kW_el Ratio between thermal and electrical determined by module design
Requirements for energy-infrastructure		

1 Upper calorific value

2 Method A is used for gas engines and turbines designed for co-generation. The energy performance is characterized by more or less fixed efficiencies. The heat efficiency may be slightly higher when applied in low temperature heating systems.

3 Method B is used for (larger) gas turbine power plants. When heat is drawn off at temperatures above 70-90°C, a decrease in electric efficiency results. This decrease is depending on the level of the useful heat temperature, so more figures can be given for annual electric generation decrease as a function of supply (draw off) temperature.

Cooling Generation Characterization

Generator type	Absorption chillers	Compression chillers
Fuel type (gas, oil, electricity, biomass)	Thermal energy (70-110℃, possibly solar heat)	Electricity
Cold source type (soil, ground water, air, air/wet cooling tower, …)	Air/wet cooling tower	Air or cooling water (5)
Cooling medium (water, indoor air)	Water	R104a (2)
Auxiliary electric energy		
- standby (W)	0	10
- nominal operation (W)	2-5% of chilling power	20
Load range (kW input power)	20-500	300 We / 300 kWe
Power range (kW output power)	10-7000	1000 W / 1000 kW th
Modulating range (min % of nominal load)	20% - 50%	20% / 50% (3)
Minimum on-time (sec)	360-900	5 s
Annual coefficient of performance (COP) [1]	0.65-0.75	2,2 - 3,2 (4)
Cost of the equipment (€/kW)	250-400	370
Requirements for energy-infrastructure	Piping shall be insulated	Piping shall be insulated

1 The annual COP may be depending on the cold source type.
2 R104a (70% of market share in EU), R407c (20%, EU), R134a (10%, EU)
3 depending on the number of compressors that can allow step-running
4 EER (Energy Efficiency Ratio)
5 As a cold thermal sink, to release heat

Thermal Energy Storage Characterization

Storage type	Water Tank	Water Tank	Phase change Water-ice	Phase Change Materials (Organic)	Phase Change Materials (Inorganic)
Storage function (heating, DHW, cooling)	DHW	Heating	Cooling	Heating (DHW)	Heating (DHW)
Typical storage purpose (year / days / hours),	Hours	Hours	Hours	Hours (days)	Hours (days)
Operating temperature (range) for (un)loading (°C)	Ca. 60 °C	40 – 90 °C depending on design temp. of heating system	0 °C	20 - 100°C depending on selected material	10 - 100°C depending on selected material
Capacity (kWh/m^3) depending on ΔT	2,3 (20K) 4,6 (40K)	2,3 (20K) 4,6 (40K)	45 (max. 50% ice)	28 – 50	45 - 75
Power range for loading (kW)	15-20 (80 – 120 lt)	Depending on size	Depending on size	Depending on size	Depending on size
Power range for unloading (kW)	0 – 40 kW (limit by DHW flow)	idem	idem	idem	idem
Thermal loss (kW) at operating temperature	0,5 W/lt (basic insulation) [1]	0,5 W/lt (basic insulation) [1]	< 0,3 W/lt (basic insulation)	0,5 W/lt (basic insulation) [1]	0,5 W/lt (basic insulation) [1]
Efficiency of loading/unloading (%) (for thermo-chemical)	---	---	---	---	---
Costs (€/kWh),	?	?	?		
Equipment cost (€/kW)	---	---	---	18-180	
Requirements for energy-infrastructure	Requires space (warm)	Requires space (warm)	Requires space (cool)	Requires space (warm) [1]	Requires space (warm) [1]

[1] When applied as a storage system in the heating/DHW system at a temperature of 60-80°C and room temperature of ca. 20 °C

Storage type	Chemical heat storage	Aquifer Thermal Energy Storage (ATES)	Borehole Thermal Energy Storage (BTES)	Energy Pile	Cavern Thermal Energy Storage (CTES)
Storage function (heating, DHW, cooling)	Heating, DHW	Heating / Cooling	Heating / Cooling	Heating, DHW cooling	Heating
Typical storage purpose (year / days / hours),	Days-Years	Months	Months	6 months	Months
Operating temperature (range) for (un)loading (°C)	Discharge: 30-200 °C Charge: 70-300 °C Depending on choice of material	Loading at 15-20	Loading at 15-20	40-50	Loading at 20-95
Capacity (kWh/m^3) depending on ΔT	150-400 (~0.5-1.4 GJ/m^3)	Up to 15 (20K)	Up to 15 (20K)	40 (15K)	60-80 (70K)
Power range for loading (kW)	Depending on size, flow rate and type of system	0-2000 kW/pair/10K	0-60 W/m	12-36	---
Power range for unloading (kW)	idem	0-2000 kW/pair/10K	0-60 W/m	10-30	Limited by HVAC installation
Thermal loss (kW) at operating temperature	After storage effectively zero.	---	---	20%	---
Efficiency of loading/unloading (%) (for thermo-chemical)	~80%	---	---	80%	---
Costs (€/kWh),	1.5-3.5	---	---		---
Equipment cost (€/kW)	---	500-800 €/kW	800-1200 €/kW	570-960	100-500 €/m³
Requirements for energy-infrastructure	Requires space	Requires presence of aquifer	Suitable geological conditions	Drilling, pumping system, heat exchangers (optional).	Suitable geological conditions

Electrochemical Energy Storage Characterization

Storage type	Lithium battery	Lead Acid battery	Zn Flow battery	Ni-Cd battery
Typical storage time (hours / days / year),	Hours/days	Hours/days	Hours/days	Hours/days
Capacity (kWh/m^3),	15-180Ah	330 Ah	360Ah	48-108 Ah
Power range (kW),	---	---	<1MW	
Energy loss (% of capacity per h/day),	5-10% per month	4-8% per month (26ºC)	---	10% per month
Efficiency of loading/unloading (%)	---	---	---	100%
Number of cycles (maximum)	2.000-3.000	500-1.000	>4.000	1.500
costs (€/Wh)	0,91-2,51	0,25	1,17	0,92-1,71
Equipment costs (€/KW)				
Requirements for energy-infrastructure				

Storage type	Zebra battery	Hydrogen storage and generation
Typical storage time (hours / days / year),	Hours/days	Days
Capacity (kWh/m^3),	32 Ah	3 kWh/m3
Power range (kW),	---	1 – 100 (1)
Energy loss (% of capacity per h/day),	0%	N.A. (2)
Efficiency of loading/unloading (%)	100%	100%
Number of cycles (maximum)	375	N.A. (3)
costs (€/Wh)	0,92	(4)
Equipment costs (€/kW)		(5)
Requirements for energy-infrastructure		(6)

1 From small size Electrolyser (1 m3/h) to large size EL (100 m3/h)
2 Depending on the flowrate of leakage through valves and connections
3 Hydrogen is generated in a EL and consumed in a Fuel Cell
4 The cost for generating 1 kWe is around 6 kWe from RES
5 H_2 LHV (3 kWh/m3), EL cost is 12000 €/Nm3/h H_2; compressor is 15000 € /Nm3/h H_2; H_2 storage 65 €/Nm3 H_2. This means: EL: 4000 € / kWh H_2; compressor 5000 €/kWh H_2, storage 22 € / Nm3 H_2
6 Piping network and all parts in contact with H2 are considered ATEX zone 2 external and ATEX zone 0 internally